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An Appreciation

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JOURNAL OF THE AERONAUTICAL SCIENCES

Volume 2 JANUARY, 1935 Number 1

High-Altitude Flying and Its Effect on the Economics of Air Transport Operation

W. Bailey Oswald, *Douglas Aircraft Company*

(Received December 4, 1934)

HIGH-ALTITUDE flying offers the only apparent method of economically meeting the present trend toward high cruising speeds. It would make possible flight at greatly increased velocities with only a small increase in operating cost per passenger mile. Indeed, with the continuation of present progress in aerodynamics, structural design, and engines, and with an increase in volume of traffic that surely should be attracted by the tremendous speed, greater safety, and excellent comfort, possible through high-altitude flying, we should expect in the near future to obtain this high-altitude transportation at a cost equivalent to or less than that at lower altitudes. The airplane, of course, will have to be especially designed and equipped for this type of flying, particularly since air travelers have rightly learned to expect convenience and comfort, and not speed alone.

Where speed is of secondary importance, however, the operation of transport airplanes at high altitudes, 20,000 ft. to 40,000 ft. and above, seems to offer no economic advantage to the airline. Freight and express airlines, where maximum economy of operation per mile rather than greatest speed is paramount, are now most advantageously operated at lower altitudes. This result follows from the necessary high power, low gross and higher structural weights, and large fuel load of the high-altitude airplane, all of which essentially reduce the pay load. Nevertheless, all modes of transportation eventually seem to give way to speed, and we can certainly look forward to flight at the higher altitudes for the accomplishment of this goal in a reasonably economic manner.

Advantages of High Altitude Operation

Advantages to be derived from the operation of a high-altitude airline are briefly: comfort, safety and reliability, ease of navigation, high speed, high economical operating speeds, increase in volume of passenger and fast mail traffic. Disadvantages of high-altitude operation are: impracticability of short flights, decrease in pay load, increased cost of flying equipment, increased maintenance costs, engineering progress insufficient, slightly increased operating cost per passenger mile with present designs for the same volume of traffic.

From the viewpoint of the transport operator, the essential question to be settled is the combined effect of all advantages and disadvantages upon the profitable operation of the airline. The operating cost per passenger mile resulting from the consideration of all tangible factors is the final criterion of the problem. These costs for airplanes of the type in use during the past five years and for airplanes of modern advanced con-

struction are computed and analyzed later. Such an investigation of these airplanes equipped with superchargers of various capacities and engines of different horsepowers permits a fairly reliable and representative picture of the economic effect of high-altitude flying. This investigation, which follows, led to the general conclusions given in the opening paragraphs.

The meteorological composition and properties of the atmosphere at high altitude, particularly in the stratosphere, make available a comfort of travel not possible near the earth. In the stratosphere there are practically no vertical currents, gusts, unsteady winds, nor clouds. Steady winds which exist can largely be used to advantage by choosing the proper altitudes at which to fly. The humidity decreases with altitude, becoming almost negligible in the stratosphere. The temperature is extremely low and constant at about −55°C. The physical characteristics of the standard atmosphere are shown in Fig. 1.

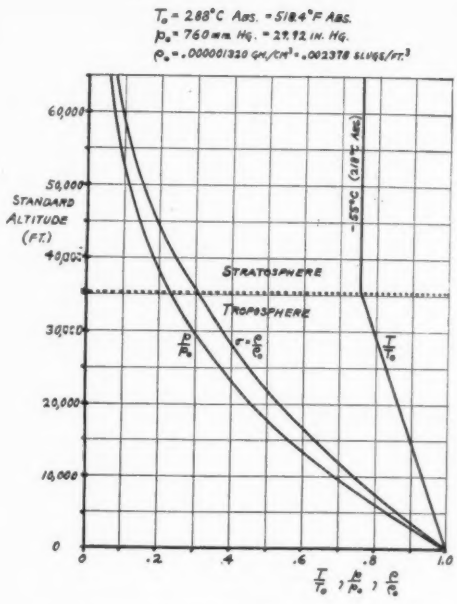

FIG. 1. Properties of the International Standard Atmosphere.

AIR PRESSURE AND TEMPERATURE

The oxygen content of the atmosphere becomes too low for comfort above about 15,000 ft. and the pressure likewise too low above approximately 30,000 ft. while in the stratosphere they are far too low for human existence. The maintenance of the required pressure and quantity of oxygen in the stratosphere presents no insurmountable problem, however. The air will have to be maintained between about 0.7 and 1.0 times sea level atmospheric pressure and circulated at the rate of approximately 20 cu. ft. of air per passenger per minute; 40 cu. ft. per minute is generally desirable, but hardly necessary. Assuming roughly 100 b.hp. per passenger and 1/7 cu. ft. engine displacement at 2000 r.p.m. per 100 hp., the engine power per passenger will require approximately 140 cu. ft. of air per minute. Since the normal intake manifold pressure of the engine at cruising is usually approximately .8 atmospheric pressure, it is seen that a 15% increase in supercharger capacity is sufficient to provide the necessary air at a satisfactory pressure. While special arrangements may require less air, it is clear that the problem of providing air for passengers at the necessary pressure is directly similar to, but secondary to, that of furnishing air to the engines.

Maintenance of the air at the proper temperature is principally a problem of controlling and regulating available heat. At the higher altitudes the air will be heated during compression to such an extent that cooling rather than heating will be necessary. At 40,000 ft. the compression will raise the temperature of the air to approximately 300°F, being correspondingly decreased and increased at lower and higher altitudes. In fact, cooling and intercooling of air by provision of proper radiative surfaces will present an interesting problem. Insulation, variable capacity radiators, and steam heating from engine exhausts provide ample capacity for temperature control; engineering will have to solve the distribution and regulation. Here again the air temperature required by the engine to insure maximum power without carburetion difficulties is approximately that desired for greatest comfort of the passengers. The temperatures might well be maintained the same. In short, by increasing supercharging capacity by 15%, or reducing the engine supercharging 15% by divert-

ing air to the passengers, adequate air will be available for passengers when the engine is correctly supercharged.

A satisfactorily leakproof cabin should not be unduly difficult to construct. Fortunately, the pressure is directed outward, giving a naturally stable structure. The fact that flying boat hulls have been built to withstand hundreds of landings without developing serious leaks indicates that an airtight design is certainly a practical possibility. At any rate, exact tightness is not necessary since air circulation must be provided. It is only necessary that any leaks be small and have no tendency to spread. Automatic control of airflow into and out of the cabin should be provided.

In high-altitude flights some passengers might find the darkened sky and reduced visibility of the earth objectionable; but high-altitude flying must be regarded purely as a means of transportation. Sightseeing will have to be done at low altitude with all its attendant evils.

Flight in the Stratosphere

Flight in the stratosphere offers nearly all that can be desired in safety and reliability. The causes of most delays in schedule and failure to complete schedule are: fog, irregular wind, and ice. These causes are not present in the stratosphere. Safety is assured by the freedom from humidity, and gusty wind, and by flying at sufficient altitude to be free from all chance of collision with obstacles such as mountains, etc. An airplane of good aerodynamic design flying at 40,000 ft. could, if necessary, glide to a landing at any point within a radius of about 120 miles. Even in the remote event that all power failed, it is quite possible that mechanics could rectify the trouble during the possible gliding time of nearly an hour in returning to earth.

Navigating an airplane in the stratosphere would be a process of convenience, ease, and accuracy. The steadiness of the winds and clearness of the atmosphere would permit the pilot to take celestial observations on the sun or stars which would always be visible, and he could thus maintain a precise course.

The chief characteristic of high-altitude operation of an airplane is the fact that for the same horsepower required to propel the airplane the velocity becomes greater as the air density decreases, hence as altitude increases. In order to illustrate the exact nature of the increase in speed with altitude the velocity ratios at full rated power and at 67% of rated power have been calculated[1] at several altitudes and plotted in Fig. 2 *versus* the design airplane parameter,

$$\Lambda=\frac{l_s l_t^{4/3}}{l_p^{1/3}}=\frac{W^2 f^{1/3}}{\text{b.hp.}_m{}^{4/3}\eta_m{}^{4/3}b_e{}^2} \quad , \qquad (1)$$

where $l_p=\dfrac{W}{f}=$ parasite loading,

$l_s=\dfrac{W}{b_e{}^2}=$ span loading,

$l_t=\dfrac{W}{\text{b.hp.}_m\eta_m}=$ thrust horsepower loading,

$W=$ weight,

$f=$ equivalent parasite area,

$b_e=$ effective span,

$\text{b.hp.}_m=$ design rated brake horsepower,

$\eta_m=$ propulsive efficiency at rated condition.

Fig. 2 shows clearly the increased velocity obtained from the same power by flying at high altitude. The dependence of the speed ratio upon Λ and the necessity of a low value of Λ for flight at high altitude is immediately apparent. Values of Λ of about 10 correspond to present high performance transport and mail airplanes while values of about 20 correspond to heavier cargo airplanes.

It is apparent from Fig. 2 that high-altitude flying furnishes an excellent means of obtaining high speed. Up to nearly the absolute ceiling of a supercharged airplane, the same horsepower

[1] Calculations follow essentially the general methods of N. A. C. A. Technical Report No. 408 and A. C. I. C. No. 679. The relations and their derivations are omitted because of space limitations.

develops higher and higher speed as altitude increases. Unfortunately this extrapolation is not endless since the minimum horsepower required increases with altitude inversely as the square root of the air density, and soon insufficient horsepower is available. This conception might be clarified by the viewpoint that the maximum rate of climb decreases with altitude, and finally goes to zero even though the horsepower available remains constant, since minimum horsepower required increases as stated above.

High speed obtained by flying at high altitudes can be obtained at a cost per mile in the same order of magnitude as the corresponding lower sea level speed, since the power/velocity ratio remains constant. For if we fly at constant indicated velocity

$$R_{v_h}=\frac{1}{\sigma^{1/2}}R_v, \text{ then } R_{p_h}=\frac{1}{\sigma^{1/2}}R_p, \text{ hence}$$
$$\frac{R_{p_h}}{R_{v_h}}=\frac{R_p}{R_v}=\text{constant}. \tag{2}$$

R_v and R_p are the velocity and power ratios respectively as defined in Fig. 2. Indeed this relation would be directly applicable if engine weight, fuel consumption, pay load, overhead costs, etc. did not enter. On the other hand, increased velocity obtained by increasing the horsepower at sea level results in a higher power/speed ratio, hence higher operating cost, since at speeds near the maximum

$$\frac{R_p}{R_v}=\frac{KR_v^3}{R_v}=KR_v^2 \text{ (approximately)}. \tag{3}$$

There is further increase in cost since increase in engine weight causes a decrease in pay load. High speeds at altitude are economical but are expensive at sea level.

Cruising speeds at 40,000 ft. altitude of the order of 175 to 275 m.p.h. are obtainable at a cost of approximately 9 to 4 cents per passenger mile. The figures refer respectively to unimproved equipment in use during the past five years and improved type modern equipment, where both are properly supercharged with turbo-centrifugal compressors. A regular 10-hour

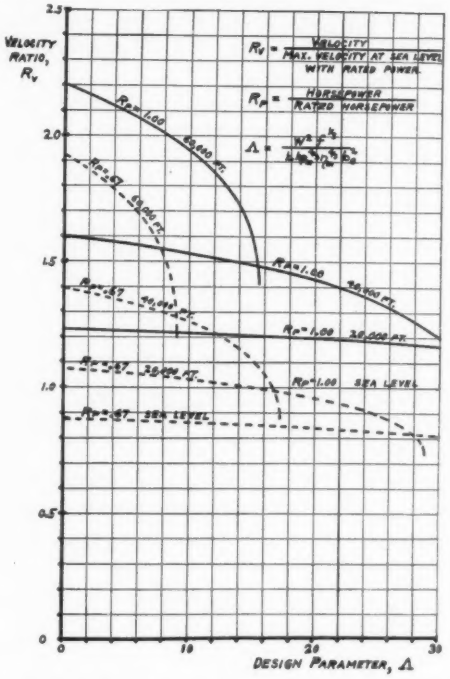

FIG. 2. Velocity Ratio R_v as a function of Δ at various altitudes for constant horsepower ratios R_p.

cross country flight becomes feasible. Such service from New York to Los Angeles at a cost per passenger of approximately $100 to the airlines, or about $125 to the passenger should certainly merit and receive patronage. A fast mail and express line might possibly operate successfully on this schedule even with the present contract mail rates.

The operation of a high-altitude airline over a short distance would be of no advantage because the airplane would not have sufficient time to reach the high operating altitude. If it should have time only to reach the operating altitude and return immediately, the average altitude would be only approximately half the highest, and the benefit thereby reduced. This suggests the use of high-altitude operation only for flights of great length. However, long flights require heavy fuel loads regardless of the altitude of flight, hence cause a decrease in pay load.

Principally for the reason of possible flights in short "hops," low-altitude operation is unequaled

purely from the standpoint of low operating cost per mile, where volume of traffic would be unchanged. Such short range service, however, is comparable to local train service, and will not receive the majority of passenger patronage. Freight and slow express can be most advantageously carried in flights of short duration at low altitude. For flights of length greater than about 600 miles, great benefit in speed may be derived by flying at the higher altitudes. The loss in time due to the slow climb is largely balanced by the gain due to the long descent in returning to land. Refueling in the air is a possible method of increasing pay load, and permits the airplane to remain at high altitude. Speed would thus be maintained, and passengers would not be disturbed at landings. Refueling in the air certainly deserves serious consideration for high-altitude flights.

Design Requirements

An airplane designed to operate at high altitudes will necessarily have a higher ratio of empty weight to loaded weight, hence lower pay load than a similar airplane designed for operating at low altitudes. A supercharger of the turbo or Roots type of 20,000 ft. capacity weighs approximately 0.4 pound per horsepower. A geared-centrifugal blower weighs somewhat less. This weight approximately doubles for each 20,000 ft. increase in supercharger capacity. A larger propeller, either with variable gearing or variable pitch or both will be necessary, and will add about 0.1 pound per horsepower at 20,000 ft., doubling with each additional 20,000 ft. of altitude. The cabin must be sealed and designed to withstand atmospheric pressure within, and practically vacuum without. This should add little weight, however, since .049 inch dural is sufficient for a 6 foot diameter cabin, and modern monocoque airplanes have cabins of this order of wall thickness. The additional weight of the cabin, temperature regulating equipment, etc., should add slightly to the structural weight. However, it is assumed that for a 40,000 ft. critical altitude airplane an increased weight, hence a decreased pay load of about 1 pound per horsepower is required. Were it not for the necessary increase in structural and engine-propeller weights, and the increased fuel load unless refueling in the air is resorted to, the high-altitude airplane could clearly be flown more economically than the low-altitude airplane because of its greater speed. The design of the special high-altitude units to low weight is therefore of prime importance.

Equipment and Maintenance Cost

Flying equipment for a high-altitude airline will cause added expense. In later calculations the added cost of a supercharger and variable-pitch propeller is estimated at $5 per horsepower for a 20,000 ft. critical altitude airplane, and doubled for each additional 20,000 ft. of supercharging. Additional cost of the structure of an airplane of $40,000 basic price is estimated to be $3000 for an airplane operating at 20,000 ft. altitude, and $6000 for one operating at 40,000 ft. Hence an airplane of $40,000 basic price would cost approximately $54,000 when equipped to operate at 40,000 ft. Although this increase in cost may seem large, the final operating cost of the airplane will be affected but little since depreciation of flying equipment forms a relatively small portion of the total operating cost.

The cost of maintenance of equipment is second in importance only to changes in pay load. Maintenance of high-capacity superchargers, large variable-pitch or variable-gear propellers, and pressure cabins might well prove difficult for the next few years at least. This equipment is comparatively new and untried. Maintenance cost of the supercharged high-altitude airplane is estimated to be roughly about 20% higher for every 20,000 feet of operating altitude than that of a corresponding airplane operating at sea level. The maintenance cost of an airplane equipped with gear-driven centrifugal supercharger would be somewhat lower.

Probably the chief reason why high-altitude flying has not been instituted up to the present time is the fact that the engineering development of high-capacity superchargers and large variable-pitch or variable-gear propellers only appears recently to be approaching the stage where this

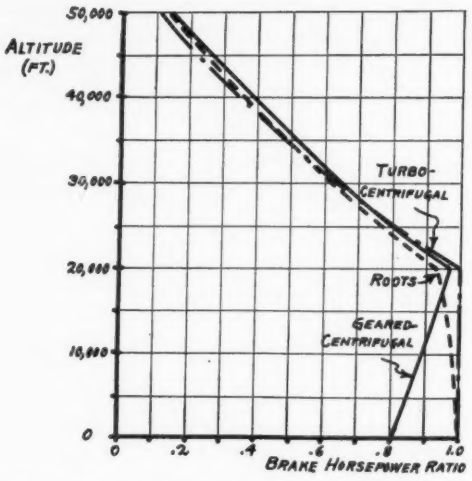

FIG. 3. Net brake horsepower of various types of supercharged engines of 20,000 ft. critical altitude. (From N. A. C. A. T.R. No. 384.) Specific fuel consumption ratio at 20,000 ft. critical altitude: Turbo = 1.00. Geared Centrifugal = 1.03. Roots = 1.08.

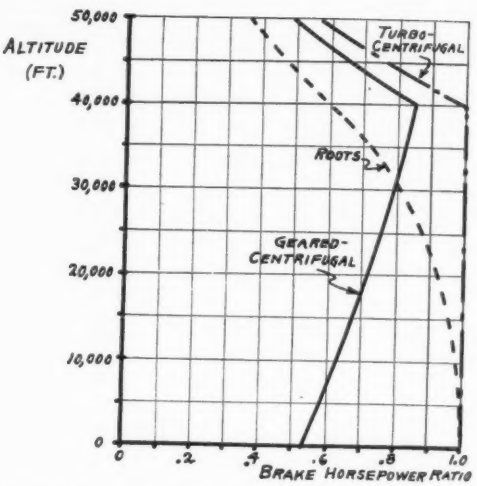

FIG. 4. Net brake horsepower of various types of supercharged engines of 40,000 ft. critical altitude. (Based on data from N. A. C. A. T.R. No. 384.) Specific fuel consumption ratio at 40,000 ft. critical altitude: Turbo = 1.00. Geared Centrifugal = 1.18. Roots = 1.69.

equipment will be both reliable and economical. The geared-centrifugal blower for critical altitudes of from 5000 to 20,000 ft. has been used with considerable success by the military services and transport companies. While this type of supercharger might be satisfactory to the air services, its high fuel consumption and reduced sea-level power makes it somewhat unsatisfactory for transport operation at high altitude. The power characteristics of the various types of superchargers are plotted in Figs. 3 and 4. The corresponding fuel consumption characteristics are given on these Figures. For the 40,000 ft. critical altitude engines it is seen that at the critical altitude the turbo-supercharger develops approximately 100% of sea-level power, the Roots 59%, and the geared-centrifugal develops 85% at 40,000 ft. and only 53% at sea level due to necessary throttling for maintaining uniform cylinder pressures. At 40,000 ft. the specific fuel consumption is 18% greater for the geared-centrifugal than for the turbo, and 69% greater for the Roots. Unfortunately up to the present time the turbo-centrifugal supercharger has offered the greatest difficulty. However, there is indication that development is now progressing satisfactorily. The high specific fuel consumption and low net available horsepower of the geared-centrifugal and Roots type of supercharged engines make them unfavorable to the economic operation of an airline at high altitude. A reliable turbo-centrifugal supercharger would be very desirable. A large variable-pitch propeller or geared propeller is necessary for successful operation of a 40,000 ft. altitude airplane in order to maintain sufficiently the climbing speed at low altitude. A multi-position pitch control is desired to meet the widely divergent conditions of flight. The varying feature is most necessary in the case of the geared-centrifugal engine since its sea-level power is low. The cost calculations carried out later assume a turbo supercharger with propeller operating at maximum efficiency at the critical altitude. This case is the optimum, and the use of any other supercharger or propeller setting would cause a proportional increase in calculated cost.

The operating costs of an unimproved airplane of the past five years and of an airplane of modern advanced construction have been computed in order to obtain a comprehensive and fairly accurate picture of the economic effects of various types of operation. The effects of increased horsepower, increased range, and high-

altitude operation have been investigated. All factors affecting operating cost, such as: overhead, depreciation, maintenance, crew mileage, decreased pay load, velocity, weight, capacity, etc., have been included in the manner and proportion believed to be most reasonable.

The basic data on costs are averages of a number of companies that were using tri-motored Boeings, Fords, Fokkers, and single-motored Boeings, Northrops, etc. Approximately half of the equipment was tri-motored and half single-motored. A table of these basic costs follows:

	Cost per airplane mile
Executive and administrative overhead	$ .042
Traffic and advertising expense	.060
Flight operations (less flying personnel)	.030
Communications: Airway (including depreciation)	.047
Communications: Aircraft (including depreciation)	.019
Rents of airport facilities and hangars	.023
Depreciation on other than flying equipment	.031
Miscellaneous expense	.020
Total overhead	.272
Insurance	.042
Depreciation of flying equipment: Aircraft	.094
Engine	.025
Total insurance and depreciation	.161
Repairs and Maintenance (including hangar expense):	
Engine replacements and supplies	.087
Aircraft	.063
Fuel and oil	.069
Total maintenance	.219
Flying personnel (pilots and co-pilots)	.102
Total operating expense	$0.754

The characteristics of the unimproved airplane represented by the above costs are assumed to be:

Price $40,000.
W = weight = 9000 lbs.,
b.hp.$_m$ = 800,
b_e = span = 60 ft.,
S = area = 600 sq. ft.,
f = equivalent parasite area = 28 sq. ft.,
W_{PL} = pay load = 2000 lbs.,
$W_{UL} = W_{PL}$ + fuel = 3500 lbs.,
c = specific fuel consumption = 0.55 lb./b.hp.-hr.,
η_m = propulsive efficiency = .80.

The parameters used for obtaining performance characteristics are:

$$l_s = \frac{W}{b_e^2} = 2.5,$$

$$l_l = \frac{W}{\text{b.hp.}_m \eta_m} = 14.1,$$

$$l_p = \frac{W}{f} = 322,$$

$$\Lambda = \frac{l_s l_l^{4/3}}{l_p^{1/3}} = 12.4,$$

V_m = maximum velocity = 145 m.p.h.;
C_O = maximum rate of climb = 935 ft./min.;
H = absolute ceiling = 18,000 ft.;
V cruising = 120 m.p.h.,
R_s cruising = .828,
R_P cruising = .62,
Range = 660 miles.

The characteristics of the improved type of airplane for which costs are computed have been assumed the same as the average airplane except that

f = 12,
W_{UL} = 4000,
W_{PL} depends upon range, etc.,
l_p = 750,
Λ = 9.35,
V_m = 193 m.p.h.,
C_0 = 1010 ft./min.,
V cruising is varied,
Range = (a) 660 miles,
(b) 1500 miles.

The various cases investigated and the results[2] obtained are given in the accompanying table, and plotted in Fig. 5.

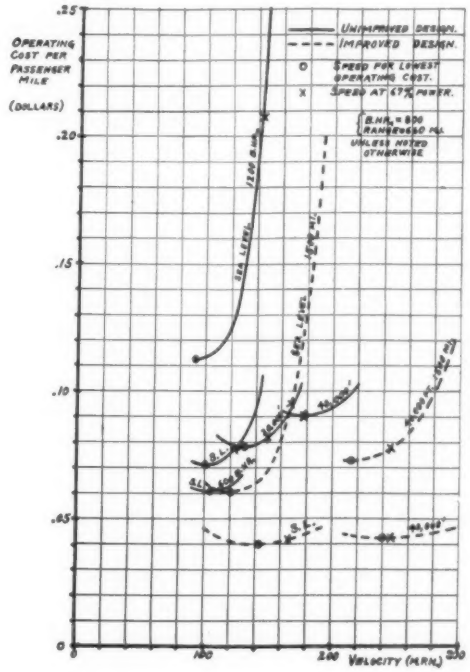

FIG. 5. Operating cost per passenger mile of a medium-sized airplane under various conditions. Figures assume full load and constant volume of traffic.

Several interesting conclusions can be derived from a study of Fig. 5 and the following table. An increase in horsepower with the same degree of

[2] The calculations and relations have been omitted because of space limitations.

TABLE OF COSTS OF OPERATION OF AIRPLANES UNDER VARIOUS CONDITIONS

Airplane and Conditions	W_{UL} lb.	Cost and Capacity	V_m at Critical Altitude	Climb at Critical Altitude	Range = 660		Range = 1500	
					Oper. Vel.	Cost per Pass. mi.	Oper. Vel.	Cost per Pass. mi.
Average Airplane. Crit. Alt. = Sea Level. b.hp.$_m$ = 800	3500	$40,000 10	145	935	90 100 110 130 145	$.0728 .0710 .0720 .0822 .1066		
Average Airplane. Crit. Alt. = Sea Level. b.hp.$_m$ = 1200. Added hp. at 2 lb./hp. at $10/hp.	2700	$44,000 6	167	1600	90 110 130 150 167	.1126 .1168 .1500 .2800 1.735		
Average Airplane. Crit. Alt. = Sea Level. b.hp.$_m$ = 600. Decreased hp. at 2 lb./hp. at $10/hp.	3900	$38,000 12	130	609	90 110 130	.0625 .0606 .0670		
Average Airplane. Crit. Alt. = 20,000 ft. Turbo-supercharged, +.5 lb./hp., $5/hp., 800 b.hp.$_m$, +20% Maintenance.	3000	$47,000 8	175	795	110 130 150 175	.0828 .0780 .0824 .1025		
Average Airplane. Crit. Alt. = 40,000 ft. Turbo-supercharged, 800 b.hp.$_m$, +1 lb./hp., $10/hp., +40% Maintenance.	2500	$54,000 6	220	532	160 180 200 220	.0923 .0903 .0835 .1026		
Advanced Airplane. Crit. Alt. = Sea Level. 800 b.hp.$_m$	4000	$40,000 15	193	1010	100 120 140 160 193	.0463 .0414 .0396 .0407 .0466	100 120 140 160 193	.064 .060 .063 .079 .200
Advanced Airplane. Crit. Alt. = 40,000 ft. Turbo-supercharged, 800 b.hp.$_m$, +1 lb./hp., $10/hp., +40% Maintenance.	3000	$54,000 9	297	690	210 230 250 270 297	.0439 .0427 .0424 .0436 .0461	210 230 250 270 297	.073 .073 .078 .091 .121

supercharging greatly increases the operating cost without increase in optimum operating speed. High operating speed at low altitude is decidedly impractical when obtained by increasing power. The effect of high altitude operation with turbo-centrifugal supercharger shows a definite increase in optimum operating velocity at a small increase in cost per passenger mile. At 40,000 ft. with the unimproved airplane a 77% increase in velocity is obtained with an increase in operating cost of 27%. The improved type modern airplane (with a 14% increase in useful load and a 57% decrease in resistance) shows betterment over the unimproved airplane by a decrease in operating cost per passenger mile of about 34% accompanied by an increased cruising velocity of 42%. Supercharging to 40,000 ft. critical altitude in this case increases operating velocity 69% with a resultant increase in cost of only 6%. The effect of an increase in range of from 660 miles to 1500 miles (128% increase) raises the cost of operation for the sea level airplane 50% and decreases the optimum speed 15%. Increased range causes the high-altitude airplane to experience a slightly greater increase in operating cost than the low-altitude airplane. All costs are based on the same volume of traffic and, of course, will be directly affected by changes therein.

The general indication is that supercharging permits greatly increased operating velocity at little additional cost, and that the effect of supercharging an airplane of advanced design is much more favorable than supercharging an unimproved airplane. Increased range and increased horsepower have both the unfavorable effects of increasing operating cost and decreasing the optimum operating velocity. An airplane flying at the condition for which the speed for lowest operating cost equals the normal cruising velocity at about 67% rated brake horsepower would be the most compatible arrangement from transport operators' viewpoint, since airlines are now operating their airplanes at about two-thirds maximum rated brake horsepower. This condition is approximately satisfied by some of the cases investigated, as reference to Fig. 5 will show. The increase in operating costs due to cruising at speeds above the optimum operating speed is very small for airplanes of advanced

design, but large for airplanes of earlier design. All factors favor generally improved designs. Application of high-capacity superchargers to airplanes of improved design results in greatly increased operating speeds at very little increase in cost per passenger mile.

The never-ceasing demand of certain types of transportation for higher cruising velocities that are at the same time economical, requires not only airplanes of generally advanced aerodynamic and structural design, but requires also flight at increasingly higher altitudes. The present development of airplanes, engines, and propellers is now laying the foundation for the economical invasion of the higher altitudes, and this invasion will surely and rapidly progress. The future of the airplane as the outstanding mode of high-speed transportation is directly connected with the altitude that can be maintained in cruising flight, and necessarily with consistent aerodynamic design for this type of flight.

Progress in aerodynamic and structural design may eventually lead to high-speed, high-altitude transportation at lower cost per mile than low-speed, low-altitude transportation, approaching rates now common for present surface modes of travel. Volume of traffic resulting from this high-speed service at high altitudes should in itself greatly aid in reducing the cost of airplane transportation.

Control Surface Flaps for Trim and Balance

A. E. LOMBARD, *Curtiss Aeroplane and Motor Co., Inc.*

(Received August 25, 1934)

WITHIN the past few years the application of small flaps to the movable control surfaces of airplanes has become extensive. That these flaps give a quick, light and highly effective control is shown by the fact that on the Curtiss-Wright "Condor" a 90° adjustment of the elevator flap control wheel changes the longitudinal trim of the airplane as much as 28 turns on the stabilizer adjustment control.

On airplanes of more than one engine the control flap on the rudder has proven to be of great assistance to the pilot when flying with one engine dead and is largely responsible for the fact that modern twin engine airplanes can be designed satisfactorily with a single vertical tail. For example, the original Curtiss "Condor", built in 1929–1930, had two fins and rudders located in the slipstreams from the two propellers to enable straight flight to be maintained on one engine. The new "Condor" is built with a single vertical tail mounted rigidly on the fuselage, and the rudder with its control flap has sufficient power to hold the airplane on a straight course with one engine out of commission.

When used to give control in lieu of an adjustable stabilizer or vertical fin, the control flap may be called a "trimmer" and when used to reduce the hinge moments of a control surface, the term "balance" is appropriate. In the following notes the theoretical formulae for the effect of these flaps are presented as well as the results of wind tunnel tests on several types of trimmers and balances.

NOMENCLATURE

α_s = stabilizer angle, see Fig. 1.
δ = elevator angle, see Fig. 1.
ϵ = control flap angle, see Fig. 1.
c_e = elevator chord aft of hinge which includes chord of inset flap.* See Fig. 1.
c_f = flap chord aft of hinge.* See Fig. 1.
c_t = overall chord of tail.* See Fig. 1.
S_e = elevator area aft of hinge including area of inset flap.*
S_f = flap area aft of hinge.*
$E_e = c_e/c_t$.
$E_f = c_f/c_t$.
β_e, γ_e, λ_e = parameters—elevator. See Eqs. (1 and 2).
γ_f, λ_f = parameters—control flap. See Eqs. (1 and 2).
q = dynamic pressure $(= \rho V^2/2)$.
C_L = Lift$/qS$.
C_{H_e} = (Elevator hinge moment)$/qc_eS_e$.

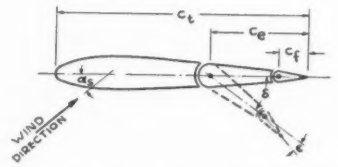

FIG. 1. Nomenclature for angles and dimensions. Positive angles shown.

THEORETICAL CONSIDERATIONS

On a normal movable control surface that is not overbalanced the moment about the hinge axis necessary to displace the surface from its neutral position increases as the angular displacement of the surface increases. Likewise the moment produced about this hinge axis by displacing the control surface flap increases with the angular displacement of the flap. The effectiveness of the control surface flap is determined by the relative magnitudes of these two moments: the moment due to the surface displacement, and the moment due to the flap displacement.

A mathematical analysis has been made by Perring[1] in which he derived the theoretical relationships of lift, pitching moment, and hinge moments for thin rectangular airfoils with multiple hinged flaps at small angles. These theoretical relationships are given below as they would apply to a rectangular horizontal tail system with a stabilizer, elevator, and control flap, each with a full span.

The theoretical equation for the lift coefficient of the tail surface is

$$C_{L_t} = (dC_L/d\alpha)_t(\alpha_s + \lambda_e\delta + \lambda_f\epsilon). \qquad (1)$$

* In the case of the tests with the external flaps, see Fig. 8, the elevator chord and area, c_e and S_e, do not include the chord and area of the flap. Also, in this case c_f and S_f represent the total chord and area of the flap rather than just the chord and area aft of the hinge.

[1] W. G. A. Perring, *The Theoretical Relationships for an Aerofoil with a Multiply Hinged Flap System*. R. & M. No. 1171 (1928).

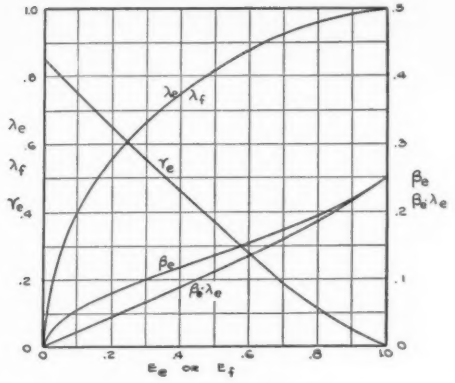

FIG. 2. Theoretical relations for thin airfoils at small angles. Elevator and control flap parameters. (*Note:* Parameters with subscript *e* are functions of E_e; parameters with subscript *f* are functions of E_f.)

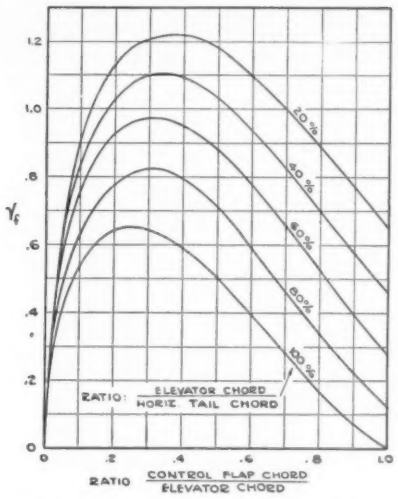

FIG. 3. Theoretical relations for thin airfoils at small angles. Control flap parameter.

In the above equation $(dC_L/d\alpha)_t$ is the slope of the lift curve, which is a function of the aspect ratio of the tail. See Higgins' report[2] for the theoretical values of this function.

λ_e, λ_f are functions of E_e and E_f, the values of which are given in Fig. 2.

The theoretical equation for the hinge moment of an elevator with a flap extending along its full span is

$$C_{H_e} = -\beta_e C_L - \gamma_e \delta - \gamma_f \epsilon. \qquad (2)$$

β_e, γ_e and γ_f are parameters, the values of which are given in Figs. 2 and 3. All angles are expressed in radians.

From Eqs. (1) and (2) above we can derive by partial differentiation expressions for the variations of the elevator hinge moment as independent functions of (1) the elevator angle, and (2) the flap angle.

Due to elevator motion:

$$\partial C_{H_e}/\partial \delta = -\beta_e \lambda_e \cdot (dC_L/d\alpha)_t - \gamma_e. \qquad (3)$$

Due to control flap motion:

$$\partial C_{H_e}/\partial \epsilon = -\beta_e \lambda_f \cdot (dC_L/d\alpha)_t - \gamma_f. \qquad (4)$$

A check of the theoretical values above has been made against actual values obtained in the wind tunnel for models of the Curtiss-Wright "Condor". On the 1/32 scale wind tunnel model

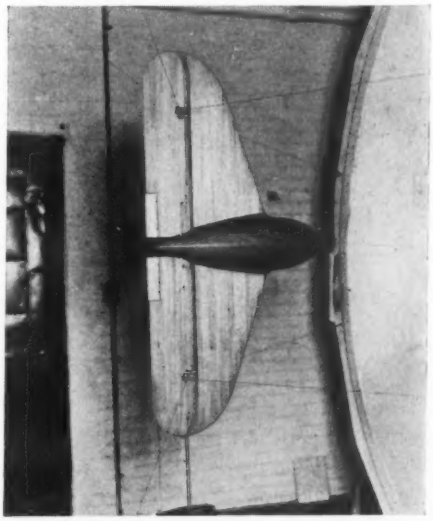

FIG. 4. 1/8 scale model of the horizontal tail of the Curtiss-Wright "Condor" with section of rear portion of fuselage attached.

of the complete airplane the observed value of $(dC_L/d\alpha)_t = 0.040$/degree. The theoretical value[2] is $(dC_L/d\alpha)_t = 0.063$. For the unbalanced elevator shown in Fig. 5 the variation of hinge moment with elevator angle is

$$\partial C_{H_e}/\partial \delta (\text{theoretical}) = -0.012/\text{degree},$$

[2] George J. Higgins, *The Prediction of Airfoil Characteristics*. N. A. C. A. Report No. 312 (1929).

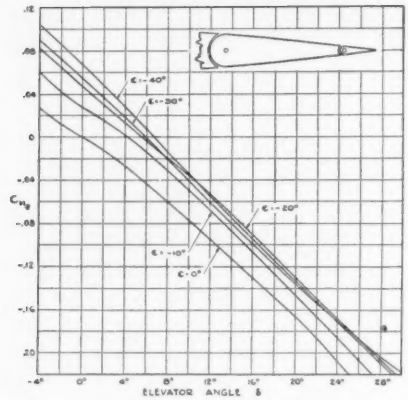

FIG. 5. Hinge moments for unbalanced elevator with inset trimming flap fixed to move with elevator. Stabilizer angle $\alpha_s = 0°$; $c_f/c_e = 0.214$; $S_f/S_e = 0.052$.

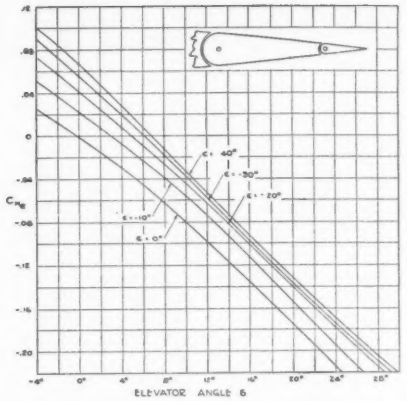

FIG. 6. Hinge moments for unbalanced elevator with inset trimming flap fixed to move with elevator. Stabilizer angle $\alpha_s = 0°$; $c_f/c_e = 0.285$; $S_f/S_e = 0.070$.

$\partial C_{H_e}/\partial\delta$(wind tunnel) $= -0.0078$ at small angles.

On the assumption that the control flap effectiveness is proportional to the control flap span, the change in elevator hinge moment with control flap angles for the elevator flap combination of Fig. 5, in which the flap is approximately 25 percent of the effective elevator span, is

$\partial C_{H_e}/\partial\epsilon$(theoretical) $= -0.0048$/degree,

$\partial C_{H_e}/\partial\epsilon$(wind tunnel) $= -0.0025$ at small angles.

[The slope of the tail lift curve from the wind tunnel is the effective slope. The slope calculated from airfoil data does not include the tail efficiency. *The Editor.*]

Thus we see that observed wind tunnel forces and hinge moments are in general from one-half to two-thirds of the theoretical values. This discrepancy is considered to be due in part to the general reduction in airfoil efficiencies below their theoretical values and in part to the disturbance caused by the portion of the tail of the fuselage present in all these tests. See Fig. 4.

The criterion for control flap effectiveness of the elevator-flap combination in Fig. 6 is:

$$(\partial C_H/\partial\epsilon)/(\partial C_H/\partial\delta) = 0.40 \text{ (theoretical)}$$
$$= 0.32 \text{ (wind tunnel)}.$$

It appears, therefore, that this theoretical value for the control flap effectiveness is in approximate agreement with the observed value in the wind tunnel. This expression for effectiveness is significant because it gives us a measure of the relative motion of the elevator for a given motion of the trimming flap.

WIND TUNNEL TESTS

Wind tunnel tests in the eight foot open throat wind tunnel of the Curtiss Aeroplane and Motor Co., Inc. were made of a 1/8 scale model of a horizontal tail for the Curtiss-Wright "Condor". This tail has a symmetrical airfoil section 9 percent thick. The principle full scale dimensions of this tail surface are:

Total area including fuselage	156 sq. ft.
Elevator area aft of hinge	51 sq. ft.
Elevator chord	28 inches
Span	24 feet 0 inch
Aspect ratio	3.7

All tests were made at 80 m.p.h. The angle of the flap to the elevator was held constant for each run and hinge moments were measured at various elevator angles. Fig. 4 gives a photograph of the model and set-up. The results are given in Figs. 5 to 9.

A comparison of the curves of Figs. 5 to 7 shows the relative effectiveness of several flaps

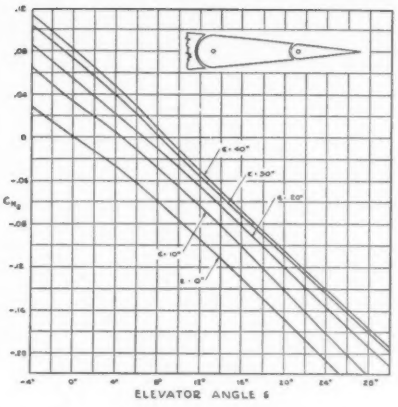

FIG. 7. Hinge moments for unbalanced elevator with inset trimming flap fixed to move with elevator. Stabilizer angle $\alpha_s=0°$; $c_f/c_e=0.429$; $S_f/S_e=0.104$.

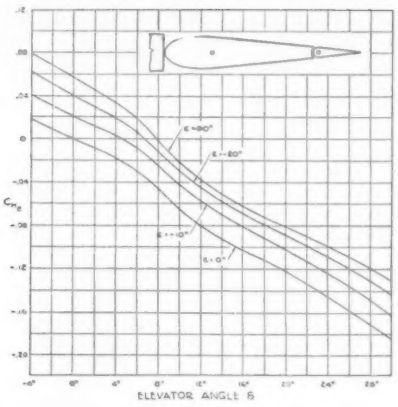

FIG. 9. Hinge moments for balanced elevator with inset trimming flap fixed to move with elevator. (Leading edge balance chord 24 percent of overall elevator chord.) Stabilizer angle $\alpha_s=0°$; $c_f/c_e=0.285$; $S_f/S_e=0.070$.

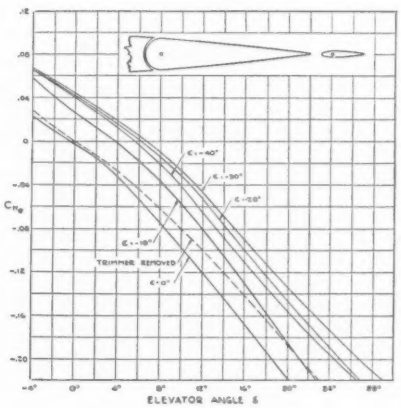

FIG. 8. Hinge moments for unbalanced elevator with external trimming flap to move with elevator. Stabilizer angle $\alpha_s=0°$; $c_f/c_e=0.285$; $S_f/S_e=0.070$. Aspect ratio of flap=4.0.

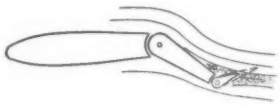

FIG. 10. Lines of flow over stabilizer-elevator-trimming flap unit at large elevator angles.

all of the same span. The flap span was held constant in these tests, rather than the aspect ratio, area, or other dimension, because it was felt that the purpose of the flap was to influence the flow of air over that portion of the elevator and stabilizer in front of it and that therefore the total "affected" area should be held constant. It is seen that the narrow chord flap, Fig. 5, contributed almost the same increase in hinge moment at zero elevator angle as the large chord flap, Fig. 7. This is as would be expected from the theoretical curve, Fig. 3, inasmuch as these flaps have chord ratios between 0.21 and 0.42 and are therefore near the peak of γ_f. However, at large elevator angles it is seen that the narrow chord flap lost its effectiveness and in fact apparently "stalled" at an angle between 30 and 40 degrees. This is considered due to the fact that the narrow chord flap was probably operating in a turbulent wake when the elevator was deflected to large angles as shown in Fig. 10.

In Fig. 8 are given the results of tests of a trimming flap mounted externally behind the elevator. Because of the fact that this external type flap was acting more as an independent airfoil than as a part of the regular surface its effectiveness was not as high as might have been anticipated at first thought. It is seen that the trimmer definitely stalled at an angle between 30 and 40 degrees. The same size flap, but of the inset type, continued to increase the elevator hinge moment up to 60 degrees.

Other tests were made of this externally mounted flap still farther back of the elevator and of the flap mounted above and to the rear of the elevator. The results were approximately

the same as those of Fig. 8 and are therefore not included.

The flap of Fig. 6 was also tested on an elevator with a leading edge balance. The results are given in Fig. 9. The increment of hinge moment due to the flap in Fig. 9 is approximately the same as that of Fig. 6 which leads to the conclusion which would be expected that the hinge moment due to the flap is independent of the type of aerodynamic balance on the elevator. Additional tests were made of this elevator-flap combination (Fig. 9) with the stabilizer set at 4 degrees to the relative wind. The results are given in Fig. 11, plotted in terms of angle of trim of the elevator, i.e., the elevator angle where $C_{H_e}=0$.

It is seen in Fig. 11 that the trimming flap is more effective when the elevator is moved to decrease the lift on stabilizer than when moved to increase the lift. This is advantageous insofar as elevator control flaps are concerned because, in general at high angles of attack of the airplane, the stabilizer is at a positive angle to the relative wind and the up elevator neutralizes the lift on the stabilizer.

In Fig. 12 is plotted a curve taken from wind tunnel tests of the complete model. By using Figs. 11 and 12 it is possible to arrive at the elevator and flap angles necessary to trim the airplane in various conditions of flight. These angles are given in Table I.

TABLE I. *Elevator and flap angles necessary to trim Curtiss-Wright "Condor" in flight. (From Wind Tunnel data, Figs. 11 and 12.)*

V m.p.h.	C_L	δ Elevator	ϵ Flap	ϵ Flap*
150	0.21	1.6°	−3°	−1.5°
130	.28	.8°	−1°	+ .5°
100	.48	−2.4°	4°	
90	.59	−5.9°	15°	
80	.75	−8.5°	30°	

Inasmuch as the control flap angle is very sensitive to the stabilizer angle, the absolute value of these flap angles is only of comparative importance but it is significant that the control flap motion of 2° derived from the wind tunnel data as the amount necessary to change the trim from 150 m.p.h. to 130 m.p.h. agrees with the motion that was observed in flight.

* Flight test data.

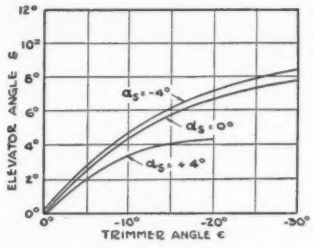

FIG. 11. Angle of trim of balanced elevator for zero stick force as affected by trimmer angle and angle of attack of stabilizer (α_s). Elevator-trimming flap configuration as in Fig. 9.

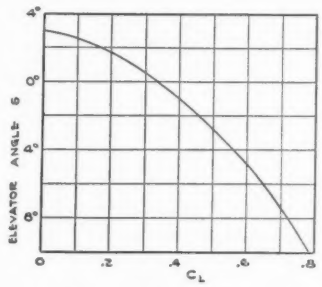

FIG. 12. Elevator angle necessary to trim Curtiss-Wright Condor with stabilizer fixed at −0.5° to wing chord c.g. at 26.5 percent. From wind tunnel tests of 1/32 scale model.

In Table I, the effectiveness of the control flap diminishes rapidly at low airspeeds and large flap angles. This is due to the reduced effectiveness of both the flap and the elevator as shown in Figs. 11 and 12. This has been observed in flight as well, as is illustrated in Table II, obtained in flights of a two-place Curtiss airplane which had both an adjustable stabilizer and an elevator control flap.

AERODYNAMIC BALANCES

In Figs. 13 and 14 are shown several types of aerodynamic balances and their comparative

TABLE II. *Airspeed for balance as function of stabilizer setting and flap angle.*

Flap angle	Airspeed, m.p.h. Stab. −2°	Stab. −6°
0°	137.0	112.0
5°	129.0	105.5
10°	122.5	101.0
15°	116.5	99.0
20°	112.0	97.5
25°	109.0	97.0

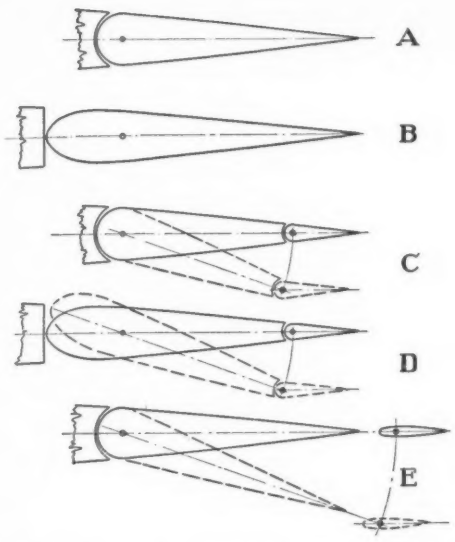

FIG. 13. Types of aerodynamic balances. *A*, no balance; *B*, leading edge balance (24 percent of overall elevator chord); *C*, inset flap balance $c_f/c_e=0.285$, $S_f/S_e=0.070$, $AR_f=4.0$; *D*, leading edge balance *B* combined with flap balance *C*; *E*, external flap balance $c_f/c_e=0.285$, $S_f/S_e=0.070$, $AR_f=4.0$.

hinge moments. The moment curves for the flap type balances were derived from the curves of Figs. 6 to 9 by drawing the curves through the points where $\epsilon=-\delta$. It is seen that the inset flap balance *C* has satisfactory characteristics, being somewhat better than the leading edge balance through the range of elevator angles up to 15°. It is in this range that aerodynamic balance is most important because, in high speed flight when the control loads require a balance, the elevator is never moved over 15°.

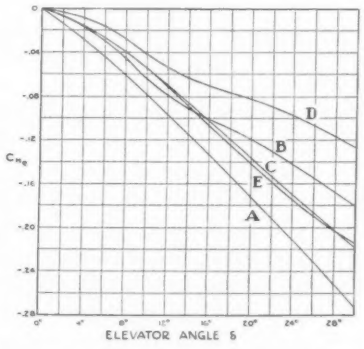

FIG. 14. Hinge moments for elevators with balances shown in Fig. 13. Stabilizer angle $\alpha_s=0°$.

CONCLUSIONS

(1) The inset type control surface flap is satisfactory to use as a controllable "trimmer" and its use has resulted in the simplification of the design of tail surfaces. The necessity of a stabilizer adjustment has been eliminated on airplanes where the elevators have been designed to have sufficient power to stall the wings. Furthermore, the use of controllable flaps on the rudders of twin engined airplanes has made it possible for such airplanes to have satisfactory directional control in single-engine flight with single vertical tails, a marked simplification over old type tails for twin engined airplanes where a fin and rudder was placed in the slipstream of each propeller.

(2) The elevator hinge moments due to an unbalanced elevator and due to a control flap as observed in the wind tunnel were approximately 60 percent of the theoretical values based on thin airfoils as small angles. The observed variation of the angle of the trim of elevator with the angle of the trimming flap was in approximate agreement, at small angles, with the theoretical variation.

(3) Wind tunnel test of inset control flaps all with the same span but with different chord dimensions indicated that, with the elevator neutral, there was little difference in the elevator hinge moment between a flap 21 percent of the elevator chord and one 42 percent of the elevator chord. However, at large elevator angles, the greater chord flap contributed a greater hinge moment.

(4) Comparative wind tunnel test of inset flaps and external flaps indicated that the two types had approximately equal effectiveness even though the inset type had a smaller moment arm.

(5) The inset type flap can be satisfactorily used as an aerodynamic balance as shown in wind tunnel tests. The balancing effect of the flap was approximately equivalent to that of a leading edge balance up to control surface angles of 15°, the maximum angle to which a control surface is genera y moved in high speed flight when the balancing effect is necessary.

A Comparison of American and European Meteorological Services

IRVING P. KRICK, *California Institute of Technology*
(Received December 6, 1934)

IN July 1933 President Roosevelt appointed the Science Advisory Board to advise the government on scientific matters and to suggest improvements wherever it seemed propitious. One of the first results was a report suggesting the adoption of more efficient methods of weather prediction by the United States Weather Bureau, namely the so-called Norwegian system of air mass and frontal analysis, which in recent years has been employed with considerable success in several European countries and by military and commercial air services in this country. The report was favorably received and considerable progress has already been made under the direction of W. R. Gregg,[1] Chief of the Weather Burea. In view of the increasing interest in meteorology in this country, particularly in connection with the new work of the Weather Bureau, the writer has undertaken to offer herein a few comments on our own and European meteorological services gleaned from observations made during a survey of the latter in the summer of 1934.

The Norwegian ideas form the basis for a great many of the daily forecasting services throughout Europe. At the present time the majority of them might be divided into three classes, namely those utilizing these methods in a manner very similar to the Norwegians themselves, those using some modification of them, and those still using empirical methods based primarily on migratory barometric pressure systems.

It is beyond the scope of the present communication to describe in detail air mass and frontal methods of weather analysis. However, to give the reader who is unfamiliar with this technique an idea of the basic principles involved, a few remarks regarding them may be in order. Let it suffice to say that they attempt to deal with atmospheric phenomena through the use of the principles of thermodynamics and hydrodynamics. It is assumed that the extra-tropical cyclones are wave phenomena along discontinuity surfaces between large bodies of air having dissimilar characteristics and that the major precipitation areas associated with them are the result of interactions between these great masses of air occurring along the discontinuities that separate them. Weather forecasting then involves first, a correct diagnosis of the current synoptic situation as indicated by the location on the weather map of air mass discontinuities or "fronts," as they are commonly called, and by the vertical structure of air masses adjacent to the fronts determined either from upper air information or by indirect methods, and second an anticipation of the propagation of the fronts and frontal phenomena during the forecast interval, together with any changes in vertical structure which may occur in the air masses involved. Since the intensity of air mass interactions along the fronts is of primary importance in forecasting, the meteorologist must determine whether or not the fronts themselves may become more or less intense during the forecast period.

METEOROLOGY AND AIRCRAFT OPERATION

As has been the experience in America, the greatest use of this type of analysis in Europe, outside of Norway, has been made in connection with aircraft operation. The reason for this, of course, is the three-dimensional nature of the analyses which permits of ready adaptation to the requirements of aviation weather prediction. As in America, the close contact of the aviation meteorologist with weather conditions has awakened in him a genuine appreciation of the Norwegian system for use in detailed synoptic work, in many instances leading to the development of a greater skill in its use than in the case of general forecasters. In most cases this has instilled into the former a much greater confidence in the methods than in the latter. The aviation meteorologist is usually obliged to construct synoptic charts at more frequent intervals than the man forecasting for fishing or agricul-

[1] W. R. Gregg, *Progress in Development of the U. S. Weather Service in Line with the Recommendations of the Science Advisory Board*. Science, Oct. 19, 1934, pp. 349–351.

tural interests. He also has a tendency to follow upper air information more closely. Such procedure leads to a correct historical sequence or continuity in his maps, a feature which is of prime importance for a successful application of air mass and frontal methods and one which the writer observed to be frequently overlooked. A lack of continuity in the maps usually results from a failure to analyze carefully each successive chart. Herein lies a great deal of the difficulty encountered by meteorologists who condemn the Norwegian methods. They make faulty analyses perhaps by forming snap judgments in an effort to complete the map quickly or perhaps by a lack of complete understanding of the theory behind the system, and, of course, predictions based upon such analyses are bound to prove erroneous since the accuracy of any forecast depends entirely upon a correct analysis or diagnosis of a given situation. Erroneous predictions resulting from faulty analyses have led in some cases to the conclusion that the Norwegian methods are poor or not applicable to the particular problems of certain localities, whereas the real difficulty usually lies with the meteorologists themselves.

Upper Air Observations Necessary

Since the vertical structure of the air masses adjacent to atmospheric discontinuities plays an important role in such analyses, a network of aerological stations for obtaining this information, covering the same territory as the surface network, is indispensible to accurate and detailed predictions. In Europe the combination of a careful analysis of surface data with upper air material is at present not entirely possible as the system of aerological stations making daily flights is confined largely to Germany. This limits the area from which upper air information is received to only a fraction of that appearing on the meteorological base charts used in plotting weather information. In addition to the stations in Germany, aerological information is also obtained from one point in England, one in Holland, and in a somewhat irregular fashion from two or three in France and one in Norway. Even on occasions when all of this information is available a very small portion of the total area occupied by the maps is covered, and many times all ascents will be found to have been made within only one type of air. For this reason, no very careful day to day analysis of upper air conditions is made by the majority of European meteorological services, and the development of thermodynamical diagrams capable of giving the data a comprehensible treatment has been slow. Since Germany has the largest network of upper air stations, one does observe at a good many forecast centers in Germany, particularly those situated at airports, an attempt to account for upper air changes from day to day. However, the treatment of the information is not so much from the standpoint of the air masses involved as from the standpoint of temperature and pressure changes due to air mass movements in the lower or higher levels of the atmosphere. The convective energy of any given mass is obtained by lifting the surface point pseudo-adiabatically on an ordinary adiabatic chart and determining the area, above the condensation level, between the original plot and the saturation adiabatic curve. The lifting of a single element in this fashion is not as helpful to the forecaster as the lifting of definite strata, a condition much more representative of actual atmospheric movements. Practically all of the thermodynamical diagrams in use in Europe at present fail to provide characteristic curves for the air masses involved or to separate the curves of different stations enough to make them distinguishable at a glance. This has been accomplished in America by introducing as coordinates, on the thermodynamical diagrams in use, conservative properties of the air masses under consideration, properties that remain constant under adiabatic or pseudo-adiabatic air mass displacements.[2] Although such charts are at present not in very general use in America, it is hoped that steps will be taken by those concerned to adopt some such thermodynamical diagram as an aid in obtaining an effective treatment of upper air information.

As might be expected, the highest degree of perfection in the physical analysis of the Euro-

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[2] C. G. Rossby, *Thermodynamics Applied to Air Mass Analysis*. Mass. Inst. of Tech. Meteorological Papers, Vol. 1, No. 3.

Allan C. Clark, *Determination of Potential Instability in Air Masses*. Calif. Inst. of Tech. Met. Dept. Prof. Notes.

pean synoptic charts has been obtained in Norway. However, the Norwegians are handicapped by a lack of upper air information. As mentioned above, the major portion of this material comes from Germany which is too far south and east of them to be of much value in many cases. This absence of upper air information necessitates the use of indirect aerology in determining the structures of various air masses encountered in the analyses. By the use of differences in sea and air temperatures over the ocean, cloud forms and types of precipitation, some estimate of the vertical distribution of certain air mass characteristics may be made, but this, of course, is not as satisfactory as having actual upper air data. In America, under the present reorganization program of the Weather Bureau, this difficulty may be largely overcome since, at the present time, we have approximately twenty stations throughout the country making daily upper air soundings. This makes free air data available from a considerable portion of the region covered by daily synoptic charts. It is the writer's opinion that America, with the development of the present plans for advancement in weather forecasting technique, will be in a position to make significant contributions to the general increase in meteorological knowledge through a combination of well analyzed upper air data with accurate and correct physical analyses.

Forecasting at Bergen

Since we ourselves are in the process of adopting the Norwegian methods, which furthermore form the basis for the majority of the best European services, a few comments on the present procedure at the weather forecasting center in Bergen, Norway, seem in order. At this point, three daily synoptic charts are constructed and carefully analyzed, one for observations at 08:00 hours, the second for those at 14:00 hours, and the third for 19:00 hours, Central European Time. The practice of drawing at least three charts daily is common to all other European meteorological services. In addition, a northern hemisphere chart is drawn for 02:00 hours, but in most cases is not as completely analyzed as the larger scale maps which contain much more complete information. At this point I might mention that the Norwegians have developed methods of predicting general weather conditions for several days in advance, based largely upon pressure tendencies. They are greatly hampered in carrying out this work by the absence of this information from the United States on the northern hemisphere charts. Professor Hesselberg, Director of the Norske Meteorologiske Institutt in Oslo, strongly urges America to adopt the International Weather Code in its present form for use in the transmission of all data in order to eliminate such difficulties and to help stimulate international cooperation between meteorological services. The Science Advisory Board, in its report, has recommended such a change, and it is hoped that it may be carried out in the near future, as the use of this code would greatly facilitate the work of American meteorologists as well as that of our colleagues abroad.

In Norway, auxiliary weather charts of pressure changes, temperature changes, movements of precipitation areas and the like, are conspicuously absent, all information being entered and treated upon one base chart in order to facilitate the correlation between the various elements involved in the analyses. The only charts which might be termed auxiliary are those used for the plotting of upper air information.

During the writer's stay in Bergen, an experiment was carried out which proved very satisfactory and which probably will form hereafter an integral part of the daily forecasting practice at this station. This work consisted of entering on the synoptic charts, in addition to the ordinary physical analysis, a kinematical one based upon recent investigations by Dr. S. Petterssen,[3] who is in charge of this forecasting center. He has developed methods for computing the movements and variations of pressure systems, fronts and their associated wave disturbances and other elements of the physical analysis which are of interest to the synoptic meteorologist in preparing a forecast. These computations may be made quickly and quite accurately for prediction intervals of 24 hours and provide the forecaster with a

[3] Sverre Petterssen, *Kinematical and Dynamical Properties of the Field of Pressure with Application to Whether Forecasting*. Geofysiske Publikasjoner, Vol. X, No. 2.

means of overcoming the difficult portion of his work in passing from the physical analysis to the prediction. It is the writer's belief that this additional treatment of the analyses marks a major step foward in forecasting technique. In the past the propagation of the frontal and pressure systems occuring on the synoptic charts and their future development was largely a matter of experience and the ability of the forecaster to make a scientific guess.

Comparative Predictions

During the introduction of this new feature on the Bergen maps, two forecasters were on duty. One would use as a basis for his predictions the method formerly employed, based only on the physical analysis and his estimate of the future development of the systems involved. The second forecaster, utilizing the kinematical analysis in addition to the physical one, would calculate as far as possible the future development during the following 24 hours. At the forecast conference which is usually held four to five hours after the reception of the map signals, each forecaster would submit his prediction based upon his independent analysis, and a discussion would ensue where differences of opinion arose. Conferences of this nature are common to practically all European services and are very valuable in locating weaknesses in the treatment of the weather charts upon which current predictions are to be based. This practice is not ordinarily followed in America at present and would no doubt prove very helpful if introduced into our meteorological services. The elapsed time between the reception of the map signals and the forecast conference brings out another point worth noting in passing. Plenty of time is devoted to the analysis of the charts to avoid errors caused by snap judgments or a casual and hurried treatment of the data. The Norwegians realize that no amount of calculation would lead to a correct prediction if the analysis forming a basis for such computations is incorrect. A properly analyzed map provides for predictions of a detailed nature up to 24 hours and for general indications to at least 48 hours, therefore the time devoted to the initial analysis becomes insignificant.

Kinematical Analysis

During the first days of this experiment at Bergen, the forecast issued to the public was prepared on the basis of the physical analysis. However, when there were differences of opinion, the prediction based upon the calculations was invariably correct, so that by the end of a fortnight, a good deal more confidence was placed in the kinematical analysis than in the estimates based on the physical analysis alone. Thus Dr. Petterssen had demonstrated to himself, as well as to the rest of us, that such a procedure was indeed of practical value. The basis for a good part of the kinematical analysis is quite simple and in view of its importance a few remarks on the underlying principles are offered here.

The field of atmospheric pressure reduced to some convenient plane of reference, usually sea-level, forms the basis for all weather charts and is the only element of the charts for which no question of representativeness arises. Petterssen has treated the factors involved in passing from a completed physical analysis to a forecast by the use of the properties of this pressure field. Throughout the work we find as a basis the well-known transformation equation

$$\frac{D\phi}{Dt}=\frac{\partial\phi}{\partial t}+\bar{q}\cdot\nabla\phi, \qquad (1)$$

which states in vector notation that the rate of change of any scalar function ϕ referred to a moving system of coordinates is equal to the rate of change of ϕ with respect to a fixed system of coordinates plus the component of velocity of the moving system in the direction of the greatest rate of increase of ϕ times the magnitude of this rate of increase.

In passing from the physical analysis of the weather chart to a forecast, the meteorologist is concerned primarily with the movements of pressure and frontal systems and their variations in intensity during the forecast interval. For example, if we wish to calculate the velocity of any isobar on the chart, we need only to substitute the pressure p for ϕ in Eq. (1) and since p is constant along an isobar and Dp/Dt becomes zero if we choose a system of coordinates moving with the pressure system under consideration, our

equation becomes

$$0=\frac{\partial p}{\partial t}+\bar{q}\cdot\nabla p. \tag{2}$$

If further we choose our x-axis normal to the isobar in question with the positive direction toward high pressure we have

$$0=\frac{\partial p}{\partial t}+q\cdot\frac{\partial p}{\partial x} \tag{3}$$

and the normal velocity of the isobar becomes

$$q=-\frac{\partial p/\partial t}{\partial p/\partial x}. \tag{4}$$

$\partial p/\partial t$ is simply the local variation in pressure and forms a part of the observational material reported by the majority of the stations in any synoptic network. For unit isobars we may put $\partial p/\partial x=1/h$, where h is the distance between two neighboring unit isobars and write

$$q=-\frac{\partial p}{dt}h. \tag{5}$$

By means of Eq. (5) one may calculate the instantaneous velocity of displacement of the entire field of pressure. If the movement of pressure centers or pressure troughs be desired, graphical methods are introduced to facilitate rapid calculation, as we must here deal with a distribution of pressure and pressure tendencies rather than with individual values.

The rate of deepening or filling of pressure centers is always of considerable interest to the forecaster and may be determined very easily since at the pressure center $\nabla p=0$ and from Eq. (1) we then have

$$\frac{Dp}{Dt}=\frac{\partial p}{\partial t}, \tag{6}$$

which states that the deepening or filling of the moving system is equal to the local pressure tendency at its center.

For computing accelerations, the second derivative of Eq. (1) with respect to time is found, which gives

$$\frac{D^2p}{Dt^2}=\frac{\partial^2p}{\partial t^2}+2\bar{q}\cdot\nabla\frac{\partial p}{\partial t}+\frac{\partial\bar{q}}{\partial t}\cdot\nabla p+\bar{q}\cdot\nabla p(\bar{q}\cdot\nabla p). \tag{7}$$

At present, however, $\partial^2p/\partial t^2$, upon which the acceleration is largely dependent, does not form a part of the observational material transmitted from stations in any weather network and the acceleration cannot be computed from a single weather chart. However, since $\partial^2p/\partial t^2$ is the curvature of the barogram, stations equipped with barographs can at least estimate the sign of the acceleration. From two or more successive charts $\partial^2p/\partial t^2$ can readily be determined and the necessary computations carried through. Usually the accelerations of pressure systems during 24 hour periods are rather small, however, and an estimate is satisfactory for practical purposes.

The movements of frontal systems may also be computed through the use of the properties of the pressure field. Along a front, the dynamical boundary condition that p_1, the pressure on one side of the front at any point must equal the pressure p_2 on the other side, is permanently fulfilled. Accordingly

$$p_1-p_2=0. \tag{8}$$

In a system of coordinates fixed to a moving frontal element we have

$$\frac{D(p_1-p_2)}{Dt}=0, \tag{9}$$

and substituting in Eq. (1) we get

$$0=\frac{\partial(p_1-p_2)}{\partial t}+\bar{q}_f\cdot\nabla(p_1-p_2). \tag{10}$$

For the instantaneous velocity q_f of a front along the x-axis, we then have

$$q_f=-\frac{\partial p_1/\partial t-\partial p_2/\partial t}{\partial p_1/\partial x-\partial p_2/\partial x}. \tag{11}$$

In general, it is convenient to choose the x-axis normal to the front at the point in question. By definition, the differences $(\partial p_1/\partial t)-(\partial p_2/\partial t)$ and $(\partial p_1/\partial x)-(\partial p_2/\partial x)$ exist at a front and eliminate the possibility of obtaining an indeterminate expression of the type 0/0.

An analytical expression for the acceleration of a front may be deduced from the same principles. Determinations of frontal accelerations are im-

portant due to their relation to increasing or decreasing frontal intensities which in turn assist the forecaster in determining probable locations where new disturbances may arise, as well as variations in the intensity of existing frontal phenomena.

Pressure Tendencies Important

From the above brief discussion of the principles underlying the kinematical analysis, it is seen that the pressure tendencies, as reported from various stations in the synoptic network, are of extreme importance. In Europe, these data are reported to an accuracy of a tenth of a millibar through the use of the International Weather Code, and very satisfactory kinematical analyses may be obtained from the smoothed isobaric and isallobaric fields. In America, however, the code word used in the transmission of the tendencies limits their accuracy to little less than a millibar. Furthermore, no pressure tendencies whatsoever are received from ships in the Pacific Ocean. Such an arrangement greatly hampers the introduction of numerical methods of prediction in America. It is understood that steps are at present being taken to overcome this condition, and it is hoped that in the near future this important information may be made available.

Ship Observations Required for Oceanic Forecasts

In view of the probable inauguration, sometime during the coming year, of trans-Pacific air service, for which the most effective methods of weather analysis known must obviously be utilized, these considerations become even more significant, as analyses of this type yield most satisfactory results over vast ocean surfaces where topographic influences are absent. Aviation forecasts become more important here than those covering land routes as the meteorological elements on such extended flights where emergency landing fields are unavailable become the primary ones. This seems to point to an extensive organization program to obtain the cooperation of shipping interests in extending their weather service even beyond the limits recommended by the Science Advisory Board. In the Atlantic this has been handled in a very effective manner by the Deutsche Seewarte in Hamburg, Germany, in connection with the German trans-oceanic service to South America. Such a program would certainly be welcomed by Pacific Coast meteorologists who have always labored under difficulties due to the absence of sufficient observational material from the vast expanses of the Pacific lying to the west.

Lateral Control at High Angles of Attack

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IN spite of the general improvement of airplane design methods and of aerodynamic research technique, the airplane designer is not much better off than his prewar predecessor in dealing with the troublesome question of lateral control at high angles of attack. Although there are available much data concerning the rolling and yawing moments of numerous types of ailerons, there are no corresponding methods of using these data. There is, for instance, no established basis for choosing between two types of lateral control devices; no way of deciding whether the one having the largest rolling moment will provide better control than the one having the smallest yawing moment; no way of deciding whether the choice will be the same for all airplanes.

Although yawing moments are brought into every discussion of aileron control, the aileron control criterion[1] that is most widely used deals only with rolling moment. It is evidently assumed that the rudder control will be sufficiently powerful to counteract the aileron yawing moment. Such dependence upon the use of the rudder is dangerous; too much responsibility is placed upon the pilot who might not only use an insufficient amount of rudder with the ailerons, but in cases of emergency might actually use opposite rudder, with disastrous results.

In addition to providing insufficient design information, the method now used does not direct research into the proper channels. The motion assumed for the calculation of control power is entirely fictitious; the simple relation between aileron rolling moment and angular acceleration of roll does not exist at high angles of attack. The difficulty is that the yawing moment of the ailerons, and the yawing moment of the airplane due to an angular velocity of roll produce a yawing velocity. This yawing velocity induces a rolling moment opposite in direction to the rolling moment originally applied by the ailerons. There is consequently a strong possibility of obtaining a final motion opposite to the desired direction. The simple criterion allows for no such reversal of motion. According to it, the airplane will always roll in the direction toward which the ailerons are turned. As a direct result of the use of the simplified control criterion, the sole aim of research has been to increase rolling moment.

AILERON ANGLE AND ANGLE OF BANK

The ability to hold the airplane in a straight flight path while flying at the highest angle of attack that the longitudinal control can maintain is the minimum requirement of lateral control. The pilot must at least be able to bring the airplane back to an even keel after a disturbance and he must, in addition, be able to damp out any lateral oscillation that results. The rate at which a straight flight path is restored is a measure of the lateral controllability of the airplane.

If the pilot's ability to hold the airplane level is to be studied, a continuous relation between the motion of the ailerons and the airplane motion must exist. Since the pilot is sensitive to angle of bank, a correlation between aileron angle and angle of bank appears to be a natural one. Under this assumption of aileron movement the maximum amplitude of the motion is limited by the aileron travel and the rate at which the ailerons are moved, that is, if the aileron angle is assumed to be five times the angle of bank, the maximum angle of bank would be 5° for an aileron deflection of 25°.

If the study of the controlled lateral motion is limited to small deviations from a straight flight path, the motion may be reduced to three degrees of freedom without appreciable error. With the addition of the terms due to the ailerons which cause moments that are functions of the angle of

[1] *Wind-Tunnel Research Comparing Lateral Control Devices Particularly at High Angles of Attack*, N.A.C.A. Report No. 419.

bank, the equations[2] of lateral motion become

$$\frac{dv}{dt}-vY_v-p\left(W+\frac{g}{D}\right)+rU=0,$$

$$\frac{dp}{dt}-vL_v-pL_p-\frac{p}{D}L_\varphi-rL_r=0, \qquad (1)$$

$$\frac{dr}{dt}-vN_v-pN_p-\frac{p}{D}N_\varphi-rN_r=0,$$

where I_φ and N_φ are the rolling and yawing derivatives due to the controls. The axes of reference assumed are "body axes" and the equations have been further simplified by the assumption that the longitudinal axis is parallel to the horizon. This approximation is close at high angles of attack, when $\tan^{-1} D/L$ is very nearly equal to the angle of attack in gliding flight.

The use of non-dimensional coefficients enables one to draw clearer conclusions as to the effect of a variation of area and length ratios, of the airplane size, and of the airspeed upon the motion. Therefore the coefficients of Equations (1) are reduced to a non-dimensional system by the method proposed by Glauert in R. and M. No. 1093. The steps taken to convert the coefficients of Equations (1) to the non-dimensional system are given in Appendix (A) of this paper.

The determinant of the coefficients of Equations (1) reduced to the non-dimensional system is

$$K=\begin{vmatrix} d-y_v & C_1\mu-d\dfrac{W}{V} & \dfrac{U}{V}\mu \\ -l_v & d^2-dl_p-\mu l_\varphi & -l_r \\ -n_v & -dn_p-\mu n_\varphi & d-n_r \end{vmatrix}=0.$$

The expansion of the determinant is in the form

$$Ad^4+Bd^3+Cd^2+Dd+E=0$$

and the coefficients of the quartic equation are

$$A=1,$$

$$B=-(l_p+n_r+y_v),$$

$$C=y_vn_r+l_p(y_v+n_r)-\mu l_\varphi+\mu n_v\frac{U}{V}-n_pl_r-\mu l_v\frac{W}{V},$$

$$D=\mu l_v\left(n_p\frac{U}{V}+C_1+n_r\frac{W}{V}\right)-l_p\left(y_vn_r+\mu n_v\frac{U}{V}\right)-\mu n_v l_r\frac{W}{V}+n_pl_ry_v+\mu l_\varphi(y_v+n_r),$$

$$E=\mu C_1(n_vl_r-l_vn_r)-\mu l_\varphi\left(y_vn_r+\mu n_v\frac{U}{V}\right)+\mu n_\varphi\left(\mu l_v\frac{U}{V}+y_vl_r\right).$$

If the airplane is to return to a straight flight path after a disturbance, all of the coefficients of the quartic must be positive. However, at high angles of attack there is a strong possibility that the coefficient E will be negative. If this is the case, the airplane will diverge rapidly from a straight flight path against the pilot's control. It will appear to him as though the lateral control had been reversed. Of the three terms of which E consists, the first and third are likely to be negative and if the numerical sum of these terms is larger than the second term, the airplane will diverge. Moreover, since l_v is larger than n_v and since, in addition, l_r is larger than n_r, both an increase in the factor μ and an increase in the rate of moving the controls will make matters worse when the aileron yawing moment derivative is in the direction to oppose the turn. Since l_v is normally about thirty times as large as n_v, the only possibility for improvement lies in the direction of making n_φ equal to zero or giving it the same sign as l_φ. The possibility of having a negative value of n_v is another difficulty that must be avoided. If n_v is negative, the airplane will roll in the wrong direction regardless of the magnitude of the rolling moment.

The problem is not completely solved by the avoidance of a divergence. The motion of return must also be sufficiently damped. In order to study the effect of increasing the aileron rolling

[2] E. P. Warner, *Airplane Design—Aerodynamics.*

and favorable yawing moments upon the motion at high angles of attack, the non-dimensional derivatives of a Bristol Fighter[3] were used. The derivatives of a Bristol Fighter are similar to those of all airplanes at the stalling angle in that n_r, the derivative depending upon damping of yaw becomes positive, n_v, the derivative of yawing moment due to yaw becomes small and the rolling moment derivatives l_r and l_v become large. The equations and their solutions are given in appendix B and the results are plotted in Fig. 1.

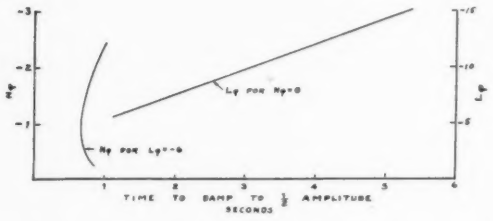

FIG. 1. Effect of aileron rolling and yawing moment upon lateral controlled motion at high angles of attack.

An examination of the curves of Fig. 1 shows that neither the increase of rolling moment nor the increase of favorable yawing moment improve control characteristics. On the contrary, the damping of the lateral oscillation becomes progressively worse as the moments are increased and the final result is an increasing oscillation. The resulting motion shows the lateral "wobble" that is typical of controlled stalled flight. The calculations indicate that no benefit can be expected from either an increase of rolling moment or an increase of favorable yawing moment if the airplane characteristics remain unchanged.

Since it was evident that the difficulty found in the previous calculation was caused by the small value of n_v and the positive value of n_r, a second set was made in which the size of the vertical tail was progressively increased. The calculation of the change of n_v and n_r due to an increase of tail size is somewhat uncertain because the vertical tail is blanketed by both the wings and the stabilizer at high angles of attack. However, for the present purpose the trend of the change is more important than its exact amount.

The equations and solutions resulting from these calculations are given in Appendix (B). The results of the calculations are plotted in Fig. 2. An examination of the results shows that an increase of vertical tail size causes a rapid decrease in the time required to damp the motion to one-half its original amplitude. In the case of the largest area assumed, the motion is damped to one-half amplitude in less than one second. The tail area was 12 percent of the wing area. This excessive amount of tail area would produce unsatisfactory characteristics at low angles of attack. However, the degree of control obtained would be considered very acceptable at high angles of attack.

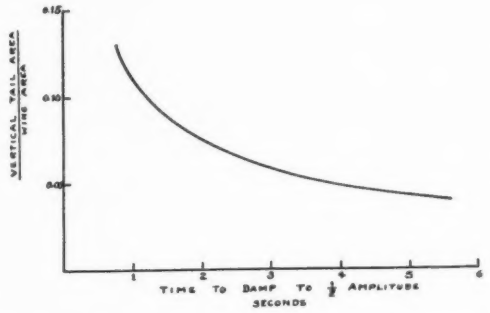

FIG. 2. Effect of vertical tail size upon lateral controlled motion at high angles of attack.

The conclusions that may be drawn from the results of these calculations are:

1. No benefit is to be derived from further research that is designed to increase rolling moment and to increase favorable yawing moment at high angles of attack.

2. More experimental data are needed for the estimation of the damping of yaw over the range of angles from the stalling angle to about 5° above the stalling angle.

3. Methods of obtaining a high value of the yawing moment due to angle of yaw at high angles of attack should be developed. This should be done without increasing the yawing moment due to yaw at law angles of attack.

[3] *Lateral Stability Calculations for the Bristol Fighter Aeroplane*, R. and M. No. 1306.

APPENDIX A

The determinant of the coefficients of the equations of motion is:

$$K=\begin{vmatrix} D-Y_v & -W-\frac{g}{D} & U \\ -L_v & D-L_p-\frac{L_\varphi}{D} & -L_r \\ -N_v & -N_p-\frac{N_\varphi}{D} & D-N_r \end{vmatrix}=0.$$

In Glauert's non-dimensional system the unit of time is defined as $T=M/\rho/2SV$ and the additional factor μ, described as the density of the airplane, is $\mu=M/\rho/2SL$, where L is the unit of length of the system. The semi-span, $b/2$, is a convenient unit of length for lateral motion calculations. The dimensional coefficients may be converted to the non-dimensional system by the following operations:

1. Multiply the second and third colums by $D=d/dt$.
2. Multiply the first line by $T=M/\rho/2SV$.
3. Multiply the second and third lines by TL.
4. Multiply the second and third columns by $T/L=\mu/V$.

If, in addition, the third column is divided by d, where $d=DT$, the non-dimensional determinant becomes

$$k=\begin{vmatrix} d-y_v & C_l\mu-d\mu\frac{W}{V} & \frac{U}{V}\mu \\ -l_v & d^2-dl_p-\mu l_\varphi & -l_r \\ -n_v & -dn_p-\mu n_\varphi & d-n_r \end{vmatrix}=0.$$

The non-dimensional coefficients l_φ and n_φ are calculated in the following manner: The rolling moment of the ailerons is

$$L_A=C_L\rho/2SbV^2,$$

where C_L is the aileron rolling moment about chord axes,

S is the wing area,
V is the velocity in ft. per sec.,
b is the wing span in ft.,
$\rho/2$ is one-half the air density in slugs per ft.^{3}.

The variation of aileron rolling moment with angle of bank is

$$\frac{\partial L_A}{\partial\varphi}=\frac{C_L}{\varphi}\rho/2SbV^2$$

and $(C/\varphi)L$ may be written

$$\frac{\partial C_L}{\partial\varphi}=\frac{dC_L}{d\epsilon}\frac{d\epsilon}{d\varphi},$$

where ϵ is the aileron angle to the wing chord. The ratio $d\epsilon/d\varphi$ describes the aileron position relative to the angle of bank. The term $(dC/d\epsilon)_L$ is obtained from a wind tunnel test of the aileron arrangement used. Using the shorthand notation for the variation of moment divided by the moment of inertia

$$L_\varphi=\frac{\partial L_A}{\partial\varphi}\frac{1}{aML^2},$$

where M is the mass of the airplane,

L is the unit of length $b/2$,
a is the non-dimensional moment of inertia factor, $a=A/ML.^2$

Then

$$L_\varphi=\frac{dC_L}{d\epsilon}\frac{d\epsilon}{d\varphi}\frac{\rho/2SV^2}{aMb/4}.$$

The term l_φ appears in the second line of the second column of the dimensional determinant and is consequently multiplied by the product $TL(\mu/V)$. After multiplication it becomes

$$\frac{2}{a}\frac{dC_L}{d\epsilon}\frac{d\epsilon}{d\varphi}\mu.$$

It is convenient to write

$$l_\varphi=\frac{2}{a}\frac{dC_L}{d\epsilon}\frac{d\epsilon}{d\varphi},$$

and the term in the non-dimensional determinant then is ul_φ.

Carrying out the same operations n_φ becomes

$$n_\varphi = -\frac{2}{c}\frac{dC_N}{d\epsilon}\frac{d\epsilon}{d\varphi},$$

and the corresponding term is μn_φ.

APPENDIX B

The non-dimensional derivatives of the Bristol Fighter at the stalling angle are

$y_v = -0.349$, $n_p = -0.228$,
$l_v = -5.17$, $l_r = 12.8$,
$n_v = 0.147$, $n_r = 0.506$,

$$l_p = -13.5.$$

The following additional data is required for the calculation:

$\alpha = 16$ degrees, G.W. $= 2850$ pounds,

$V = 74$ ft. per sec., $A = 1700$ slug ft.^{2},

$U = 71$ ft. per sec., $C = 2900$ slug ft.^{2},

$W = 20.4$ ft. per sec., $a = 0.0494$,

$\frac{W}{V} = 0.276$, $c = 0.0844$,

$\frac{U}{V} = 0.959$, $C_1 = -1.08$,

$T = 2.48$ secs., $\mu = 9.32$.

Equations of motion and their solutions. The effect of a variation of the rolling moment derivative, l_φ, is given by the following equations:

$$l_\varphi = -6, \quad n_\varphi = 0,$$
$$d^4+13.3d^3+71.1d^2+41.2d+11.4=0,$$
$$d=-6.41\pm4.89i, \quad d=-0.30\pm0.28i,$$
$$l_\varphi = -10, \quad n_\varphi = 0,$$
$$d^4+13.3d^3+108.4d^2+35.3d+49.5=0,$$
$$d=-6.5\pm7.9i, \quad d=-0.11\pm0.68i,$$
$$l_\varphi = -15, \quad n_\varphi = 0,$$
$$d^4+13.3d^3+155.2d^2+27.9d+96.75=0,$$
$$d=-6.6\pm10.4i, \quad d=-0.064\pm0.76i,$$
$$l_\varphi = -20, \quad n_\varphi = 0,$$
$$d^4+13.3d^3+201.6d^2+20.6d+144=0,$$
$$d=-6.41\pm4.89i, \quad d=0.027\pm0.841i.$$

The effect of a variation of the yawing moment derivative, n_φ, is given by the following equations:

$$l_\varphi = -6, \quad n_\varphi = -1.2,$$
$$d^4+13.3d^3+71.2d^2+185d+579.9=0,$$
$$d=-6.17\pm4.25i, \quad d=-0.50\pm3.23i,$$
$$l_\varphi = -6, \quad n_\varphi = -2.4,$$
$$d^4+13.3d^3+71.2d^2+329d+1145=0,$$
$$d=-6.20\pm2.47i, \quad d=-0.45\pm4.82i,$$
$$l_\varphi = -6, \quad n_\varphi = -3.6,$$
$$d^4+13.3d^3+71.2d^2+472.2d+1710=0,$$
$$d=-8.9, \quad d=-5.4, \quad d=0.50\pm6.0i.$$

The effect of increasing the size of the vertical tail is given by the following equations:

$$\frac{S''}{S}=0.08, \quad n_v=1.5, \quad n_r-0.80, \quad l_\varphi=-6, \quad n_\varphi=0,$$
$$d^4+14.7d^3+101.3d^2+273.9d+751=0,$$
$$d=-5.07\pm6.01i, \quad d=-0.95\pm3.35i,$$
$$\frac{S''}{S}=0.12, \quad n_v=2.87, \quad n_r=-2.11, \quad l_\varphi=-6, \quad n_\varphi=0,$$
$$d^4+16d^3+131.4d^2+492.5d+1174=0,$$
$$d=5.77\pm5.22i, \quad d=-2.19\pm3.79i.$$

Editorial Note. The conclusion of this original paper is that no further benefit is to be derived from increasing the rolling moment and favorable yawing moment of the ailerons at high angle of attack. This is at variance with the commonly accepted view. The basis of the analysis is that the ailerons are always actuated in exact proportion to the angle of roll from the normal. Only in the case of an automatic pilot could this be true. The actual method which the pilot would employ in coming back to an even keel would not be of this perfectly automatic character. If a more extended analysis were made, it might still appear that a favorable yawing moment and an increased rolling moment are desirable. Nevertheless the treatment is so stimulating and so likely to provoke worth while thought, that presentation of the study needs no apology.

Notes on the Design of Metal Wing Spars

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(Received September 26, 1934)

THE purpose of this paper is to trace briefly the development of a particular type of duralumin wing beam construction and to present the results of a series of tests which were made to obtain the basic data required for the design of this type of beam.

The original problem was to design metal wing surfaces for an existing biplane of wood construction. Metal covering could not be justified on the basis of weight, cost and ease of inspection and maintenance, therefore a two-spar fabric-covered construction was indicated. After a preliminary investigation of both steel and duralumin designs a decision was reached to use a duralumin construction. Since the spars were relatively shallow, ranging from 7 inches to 5 inches in height, it was thought that a latticed truss construction would be unsatisfactory on account of the large number of members required and the sacrifice in stiffness as compared with a plate girder.

These two considerations served to concentrate attention on the design of a plate girder spar of duralumin construction. The next question was, should it be a box beam or a single-web type? Box beams have been favored by many designers because they are relatively strong in torsion and resistant to lateral buckling. They are open to criticism, however, on two counts: first, they are more difficult and hence more

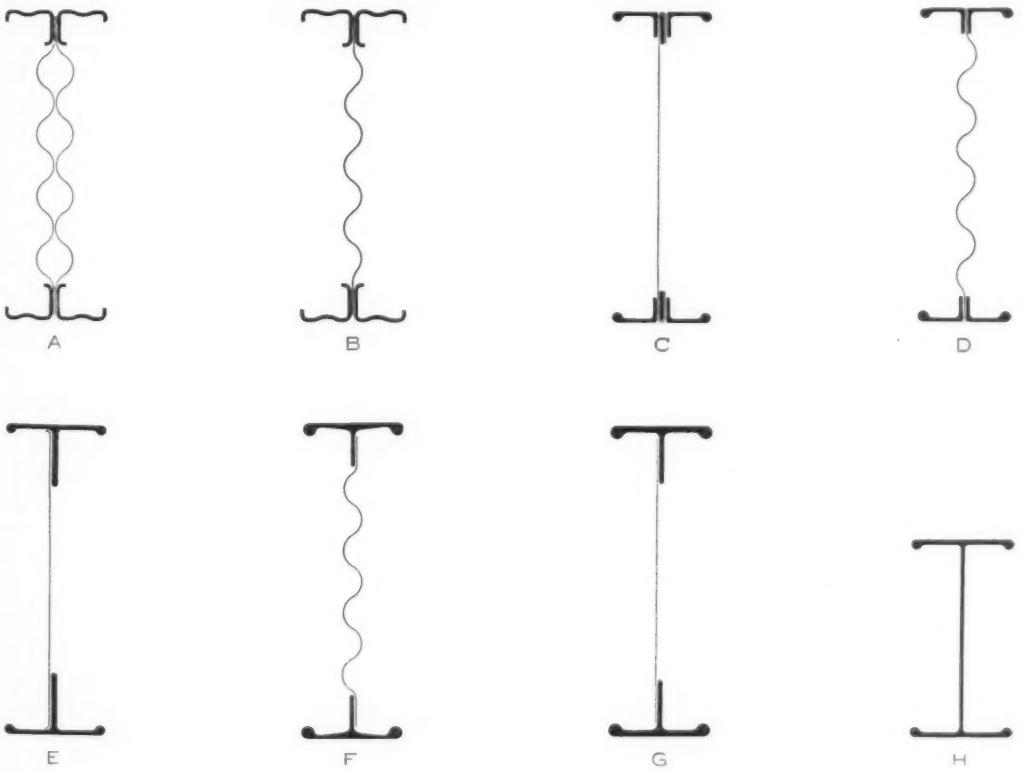

FIG. 1.

TABLE I.

Beam	*A*	*B*	*C*	*D*	*E*	*F*	G_1	G_2	G_3	*H*
Material	17-ST	17-ST	17-ST	17-ST	17-ST	17-ST	24-ST	24-ST	24-ST	24-ST
Effective (Test) *E*	9600000	9520000	10050000	10210000	10460000					
E for calculation			10000000	10000000	10000000	9000000	10000000	10000000	1000000	1000000
Area sq. in.			.6202	.600	.7626	.868	.8906	.612	1.063	.7311
I in.^{4}			5.605	4.36	6.133	4.067	6.74	2.4	7.779	1.992
Height in.			6.25	6.25	6.25	5.062	5.812	4.25	5.875	4.00
Yield point test values										
B.M. stress f_b			2870	2490	2610	10200	19900	25800	8700	25400
P stress			21780	21000	20330	13800	14450	9830	26500	9830
Total f_t			24650	23490	22940	24000	34350	35630	35200	35230
Ratio f_b/f_t			.116	.101	.114	.425	.580	.723	.250	.720
Yield point computed										
B.M. stress f_b			2520	2610	2290	9310	21100	27750	8500	29050
P stress			21780	21000	20300	13800	14450	9830	26500	9830
Total f_t			24300	23600	22590	23110	35550	37580	35000	38880
Ultimate test values										
B.M. stress f_b			8810	8530	6850	22800	34200	38400	16450	40000
P stress			31440	33330	29900	19280	18770	12000	35850	11830
Total f_t	32500	32950	40250	41860	36750	42080	52970	50400	52300	51830
Ratio f_b/f_t			.219	.202	.187	.541	.64	.76	.315	.77
Ultimate computed										
B.M. stress f_b			3230	4590	3440	17920	30250	38800	11940	43000
P stress			31440	33330	29900	19280	18770	12000	35850	11830
Total f_t			34670	37920	33340	37200	49020	50800	47790	54830
Ultimate stress in pure bending						38900		51100		
Material test—Ultimate							69050	66325	69000	65990

costly to assemble; second, they usually have a section more or less completely closed which is more likely to experience trouble from corrosion than is an open section. The latter point is of particular concern in airplanes which are operated at sea.

SINGLE-WEB TYPE OF CONSTRUCTION

Torsion tests of complete wing surfaces demonstrated that the torsional rigidity contributed by the spars was secondary to that obtained by the use of double drag bracing. Consequently, great torsional strength in the spar itself when double drag bracing is used was not essential. It was believed also that the wing ribs in themselves in conjunction with a metal leading edge and strong drag ribs, all well secured to the spar, would provide adequate support for the spar against lateral buckling. The additional fact that the single-web type of construction lends itself to convenient attachment of ribs and double drag truss bracing determined the choice of this type of spar.

The next step was to study the numerous ways that were suggested of building a single-web spar and to build and test an eight foot long specimen of the more promising designs. Five beams were fabricated having typical sections as shown on Fig. 1, beams *A* to *E* inclusive. To obtain comparative data, all specimens were made $6\frac{1}{4}$ in. high and were statically loaded in the same manner. The webs of all the specimens were stiffened by vertical angles or channels not shown on the sketches. The material in each case was The Aluminum Company of America's aluminum alloy designated as 17-ST and having a minimum yield point stress of 30,000 pounds per square inch, and a minimum ultimate tensile strength of 55,000 pounds per square inch. The results of these five beam tests are tabulated in Table I, Beams *A* to *E* inclusive.

Calculation Procedure

The *Effective Modulus of Elasticity* of each beam was obtained by a preliminary bending test of the specimen in which the applied loads were kept below the yield point and the effective E was calculated from the slope of the deflection curve. The beams were then tested to destruction under combined axial and bending loads. The maximum fibre stress in bending was calculated by using the moment of inertia of the entire cross-section in the formula, $f_b = M_y/I$. The area used in computing the direct stress was the area of the flanges plus a two inch depth of web for the flat web beams and the total web area for the corrugated web beams. The total bending moment was obtained by adding to the moment caused by the vertical loads, the secondary moment produced by the product of the axial load and the observed deflection. The maximum fibre stress was determined for both the yield point loading and the ultimate loading. The yield point loading was assumed to be the point at which a permanent set was observed in the beam. This point was also checked by plotting the maximum bay deflection against applied load and noting the point of sudden departure from a smooth line. In these beams the yield point was rather sharply defined which was not the case in the full length beams subsequently tested. In order to compare the fibre stresses calculated from the observed deflections with those given by theory, the maximum fibre stress under the yield point and ultimate loads were also calculated by a precise method taking account of secondary bending stresses. A value of 10,000,000 pounds per square inch for E was used.

Test Results

The results of the tests clearly indicated that the extruded flanges were far superior to the rolled section flanges. The test data from specimens C, D and E were close and after a careful study was made, it was decided to use a corrugated web due to the higher ultimate stresses obtained which it is believed was principally due to the web taking a larger share of the axial load. The type of beam shown as F in Fig. 1 was chosen for the airplane.

To check the design data, a full length upper front beam was fabricated and tested under conditions simulating the loads on the beam for the high angle of attack condition. In addition to a series of vertical loads representing beam air loads, end loads were applied at the strut point representing the loads from the lift truss and at the intermediate drag strut points representing the loads applied by the anti-drag wires. The results of this test are included in Table I under beam F, and confirm the conclusions drawn from the short beam tests.

A comparison of the fibre stresses calculated from the observed deflections of this beam with those computed by the precise method shows a very close agreement at the yield point load but a greater disparity at ultimate load. The deflection at ultimate load was greater than calculated by theory even though a supposedly conservative value for E of 9,000,000 was used, indicating that the effective modulus of elasticity diminishes above the yield point and that deflections due to shear were important enough to warrant consideration.

Comparison of Weight of Wood and Metal Spars

Since the wings for which these spars were designed are interchangeable with those of a wing of wooden construction, a comparison of the weights of the spars with those of the wooden wings is in order. To obtain a fair basis of comparison, the weight of the metal fittings, such as hinge and strut fittings, attached to the beam have been included in the weights. As shown in the table below, the metal spars were substantially lighter in weight even though the gross weight of the airplane and the design load factors were slightly higher in the case of the metal beams.

	Metal wing	Wooden wing
Upper front spar (lbs.)	17.1	23.1
Upper rear spar (lbs.)	16.5	23.9
Lower front spar (lbs.)	17.2	21.6
Lower rear spar (lbs.)	23.8	28.5
H. A. A. Load factor	10.1	10.0
L. A. A. Load factor	10.1	7.5
Inverted load factor	−5.4	−4.0
Gross weight of airplane (lbs.)	4600	4500

Beams with Plain Webs

Experience with this type of beam construction brought out the fact that the corrugated web did not lend itself to the maximum of simplicity in the design of attaching fittings and on a subsequent design of metal wings for a different airplane, the corrugated web was abandoned in favor of a plain web as shown in Section *G* of Fig. 1. Tests were made on three full length beams of this design—two of which were designed for a constant chord biplane, the third for a biplane with tapered wings. The results are given in Table I under beams G_1, G_2 and G_3 respectively. These beams were made from the Aluminum Company of America's aluminum alloy 24-ST, having a minimum yield strength of 40,000 pounds per square inch and an ultimate strength of 62,000 pounds per square inch. The lower rear beam of the constant chord wing was too shallow to make it worth while to use a girder so a simple extruded *I* section, shown as section *H* in Fig. 1, was used. This beam was also made of the 24-ST alloy and the results of the full length beam tests are given in the table.

As for the preceding tests, the maximum fibre stresses in the beams at yield point loads and ultimate loads have been calculated, the maximum bending stresses being obtained from the observed deflections and also by the use of the "precise" method. The moment of inertia of the entire cross section was used; the area was the area of the flanges plus a two inch depth of web except for beam *H* where the area of the entire web was taken because it had a thickness of .090 in. On beams *G*1, *G*2 and *G*3 the webs ranged from .032 to .040 in. in thickness and could not be depended on to take much compression once they began to buckle under the shear loads. The modulus of elasticity was taken as 10,000,000 instead of the 9,000,000 which was used in the calculation of beam *F*.

The maximum fibre stresses calculated from the observed deflections are in fair agreement with those computed by the precise method and are consistent among themselves within the probable limits of testing procedure and variations of physical properties of the material. The fibre stresses developed in these 24-ST beams were much higher than were found in the 17-ST beams, an improvement which was naturally expected from the stronger material.

Correlation of Fibre Stresses Developed in Beams with Physical Properties of Material

It is regretted that the physical properties of the material in each of the beams were not obtained from specimens cut from the beams. The ultimate tensile strength of the material in beams *G*1, *G*2 and *H* was obtained and is given in the table. The yield strength was measured on two samples cut from beam *G*3. To obtain accurate information on the shape of the stress-strain curves, an unusually long specimen was used, and elongations were measured on a gage length of 14 inches. By definition in the Government Specifications covering this grade of material, the yield strength is the stress at which a permanent set of .002 inches per inch is recorded or at the stress at which the extension under load is .0060 inches per inch for a specified yield strength of 40,000 pounds per square inch and .0070 inches per inch for a specified yield strength of 50,000 pounds per square inch.

The two samples showed yield strengths of

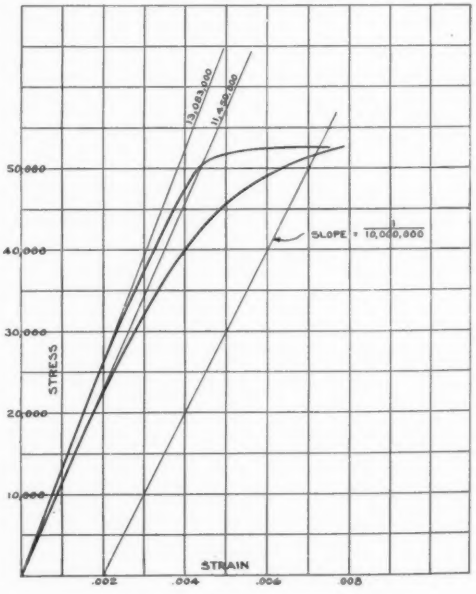

Fig. 2.

51,500 and 52,500 pounds per square inch but had quite differently shaped stress-strain curves. The first had a proportional limit at about 17,000 pounds per square inch and an initial E of 11,450,000. The second had a proportional limit at about 25,000 pounds per square inch and initial E of 13,080,000 and a nearly straight line curve to about 50,000 pounds per square inch. The curves are shown in Fig. 2 and are suggestive of the difficulties to be encountered in attempting to correlate the results of beam tests with such variations in the physical properties of the material.

Furthermore it is difficult to determine the yield point of the beams with the equipment ordinarily available. The beams seldom show a definite yield point and it is uncertain where to establish the point of first permanent set because an observed deflection of say 0.01 inch after the load has been removed may well be caused by some friction in the guides which has prevented the beam from returning perfectly to its original position. In these beams, however, it happens that the determination of the exact yield point is not a matter of primary importance. The beams are designed to make good a certain load factor at ultimate strength. This factor includes an actual factor of safety on the maximum load to which the beam is expected to be subjected in service. The yield strength of these beams is a relatively high percentage of the ultimate strength and hence the beams should be safe from danger of showing a permanent set in normal service.

The tests cover a fairly wide range of ratios of bending stress to total stress and the results obtained appear to indicate that for this type of beam the fibre stress at ultimate load is independent of this variable. This is further supported by tests in pure bending made on the overhang portions of beams F and $G2$ where moduli of rupture of 38,900 and 51,100 pounds per square inch were obtained on the 17-ST and 24-ST beams respectively. However it is felt that these tests are not sufficiently comprehensive to warrant a final conclusion on this point.

Conclusion

In general, it is felt that while these tests do not cover the field as completely as might be desired, they do provide the data by means of which the strength of beams of this type can be predicted with reasonable accuracy.

Application of Kármán's Logarithmic Law to Prediction of Airship Hull Drag

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AFTER experiments had shown that the power law theory of von Kármán and Prandtl, for the skin friction of a pointed flat plate in a two-dimensional flow parallel to the surface and perpendicular to the leading edge, could be used satisfactorily in determining the skin friction at the curved surface of a streamline body in a two-dimensional flow when the radius of curvature is large compared to the boundary layer thickness, Jones, Dryden and Kuethe extended the theory so as to give an account of the skin friction acting on a dirigible model in an axial flow. In both these discussions the dirigible was replaced by an "equivalent flat plate."

Although Boltze had given the equations for the laminar boundary layer for a body with axial symmetry about an axis in the direction of flow, and Levi-Civita had attacked the general problem of the turbulent boundary layer for a body of any shape, it remained for Millikan[1] to give a satisfactory analysis applicable to dirigible models.

Millikan derived the approximate form of the boundary layer equations in the neighborhood of the surface of a figure of revolution from the Navier-Stokes and continuity equations for the steady motion of a viscous incompressible fluid, letting the kinematic viscosity go to zero and neglecting powers of the square root of the kinematic viscosity higher than the first. The resulting equations are valid when the boundary layer thickness is small compared to its distance from the axis. In the turbulent boundary layer, Millikan assumed the one-seventh power law for the velocity profile. However, von Kármán has shown that *the power law* is merely an *interpolation of* or approximation to *the logarithmic law;* and experiments, especially those of Nikuradse, show that the 1/7th power does indeed become a 1/8th power, then a 1/9th power, etc., as the Reynolds' Number increases.

Both Millikan and von Kármán[2] have pointed out the desirability, where the analysis is to be used to predict drag coefficients at large Reynolds' Numbers, of extending Millikan's work by introduction of the logarithmic law.

As a preliminary step, Millikan's equations were generalised to hold for a $1/n$-th power law for the velocity distribution, and drag coefficients were calculated for several values of n for the N. P. L. Long Model at a large Reynolds' Number. The differences in the drag coefficients for the various power laws were found to be sufficient to justify the further refinement of introducing the logarithmic law. It was then *assumed that the logarithmic velocity distribution, as developed by von Kármán for the boundary layer on the flat plate, holds also for the boundary layer on the axially symmetric body.*

Accordingly we introduce the logarithmic velocity distribution[3]

$$u \doteq U - \frac{V_r}{\kappa(2)^{\frac{1}{2}}} \log_e (\delta/y) \qquad (1)$$

into Millikan's basic Eq. (10):

$$\tfrac{1}{2} V_r^2 = UU'\delta + (1/r_0)(d/dx)\left[r_0 \int_0^\delta u(U-u)dy \right] - U' \int_0^\delta u dy, \qquad (2)$$

where u = velocity in the boundary layer, U = velocity just outside the boundary layer, $V_r = (2\tau_0/\rho)^{\frac{1}{2}}$ = the "friction velocity," τ_0 = shearing stress at the surface, ρ = mass density, κ = von Kármán's universal constant of the turbulent exchange, δ = boundary layer thickness, y = distance normal to the surface, $U' = dU/dx$, x = distance along the surface measured from the stagnation point, and r_0 = radius of the surface of revolution.

It is found convenient to introduce a parameter z satisfying the relations

$$V_r = \kappa(2)^{\frac{1}{2}}(U/z) = [\nu/(C_2\delta)]e^z, \qquad (3)$$

where ν = kinematic viscosity, and C_2 = a constant.

Eq. (2), after carrying out the indicated operations and introducing the parameter z, can be put

in a form allowing integration with respect to x. With $\kappa=0.397$ and $C_2=10.84$, and after introducing the Reynolds' Number $R=U_0L/\nu$ (where U_0=axial velocity of the flow far from the surface and relative to it, and L=axial length of the body), and $a=x(1-r_0'^2)^{\frac{1}{2}}\equiv x\beta$, the expression resulting is

$$\zeta(z)=0.959R\int_0^{a/L}[(U/U_0)/\beta]d(a/L)+\int_0^{a/L}ze^z[2\xi(Ur_0/U_0L)-z\xi(U^2r_0/U_0^2L)]d(a/L), \quad (4)$$

where $\zeta(z)=(z^2-4z+6)e^z-6$, and $\xi(\ )$ is an operator,

$$\xi(\ )=\frac{d(\ )}{d(a/L)}.$$

r_0/L and β as functions of a/L are known from the shape of the dirigible, and U/U_0 is obtainable from wind tunnel tests. A table of $\zeta(z)$ *vs.* z was made up for values of z between 7.0 and 20.0, in steps of 0.1, allowing rapid solution of the transcendental equation $\zeta(z)=const.$ with a maximum error in z of ±0.05. The integrals involved in Eq. (4) are conveniently handled by an integraph machine. Eq. (4) is treated by a method of successive approximations, and a second approximation is found to be sufficient for a very good estimate of the drag coefficient.

The boundary layer thickness and surface shearing stress are found from Eq. (3) to be, respectively,

$$\delta=0.164\frac{Lze^z}{(U/U_0)R}, \quad \tau_0=0.158\rho U^2/z^2. \quad (5)$$

The drag coefficient, defined by

$$C_V=(\text{skin friction})/(\tfrac{1}{2}\rho U_0^2V^{\frac{2}{3}})=\frac{\int_0^L 2\pi r_0\tau_0 da}{\tfrac{1}{2}\rho U_0^2V^{\frac{2}{3}}},$$

is given by

$$C_V=1.98(L^2/V^{\frac{1}{3}})\times\int_0^1[(U/U_0)^2(r_0/L)]/z^2\cdot d(a/L). \quad (6)$$

An interesting application and check of the present theory is afforded by the U.S.S. Akron and the U.S.S. Macon. The hull drag coefficient curve, calculated with the aid of Freeman's[4] wind tunnel measurements on a model of the Akron hull, is plotted in Fig. 1, and is compared with Millikan's curve. (Note that C_V is plotted not against R, but against $R_V=U_0V^{\frac{1}{3}}/\nu$.) Experimental points for several models are also plotted: those from the N.A.C.A. propeller research tunnel (P.R.T.) and the N.A.C.A. variable density tunnel (V.D.T.), and from the ten-foot tunnel of the Guggenheim Aeronautical Laboratories at the California Institute of Technology (G.A.L.C.I.T.). The general agreement of the trend of the points with the present theory is quite satisfactory, notably so in the case of the points for the wooden model in the variable density tunnel.

There have been numerous deceleration tests made on both the U.S.S. Akron and on the U.S.S. Macon to determine their equivalent parasite areas. These were carried out at Reynolds' Numbers between 4×10^8 and 5.5×10^8. An estimate of the equivalent parasite area* f for the hulls alone, based on these tests, gives an area between $f=42m^2(C_V=0.0119)$ and $f=47m^2(C_V=0.0133)$. ($V^{\frac{2}{3}}=3530$ square meters for the Akron and Macon.) This estimate may, however, be in error by as much as 20 percent, due to the uncertainties involved in deceleration tests, and to the possible errors in estimating the hull drag from the drags of the complete ships. Nevertheless, at $R=5\times10^8$, or, $R_V=1.23\times10^8$, the curve in Fig. 1 based on the present theory gives $C_V=0.0130$ ($f=46m^2$), whereas Millikan's curve gives only $C_V=0.0100$ ($f=35m^2$). These

* Equivalent parasite area $f=(\text{drag})/(\tfrac{1}{2}\rho U_0^2)=C_VV^{2/3}$.

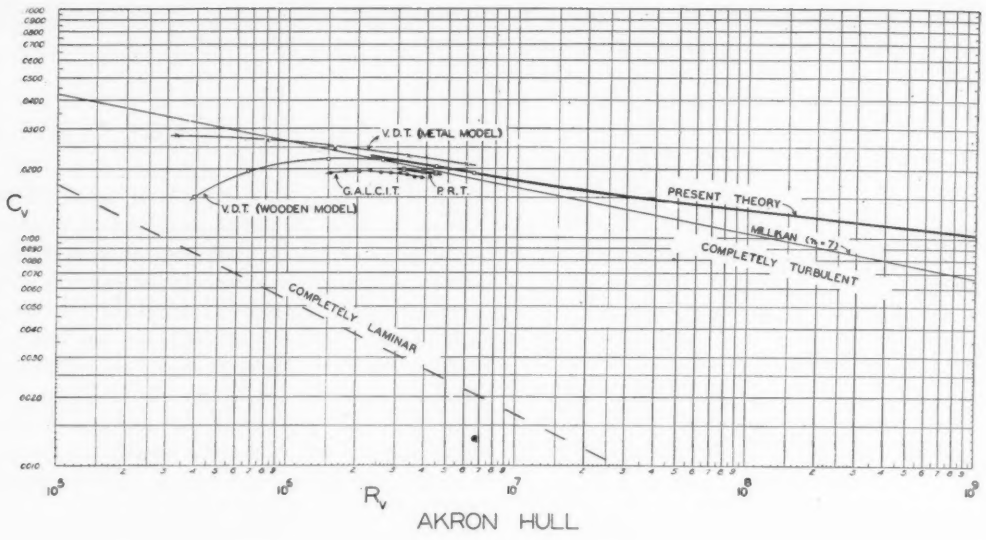

FIG. 1.

figures would thus appear to favor the extrapolation based on the logarithmic law, rather than that based on the 1/7-th power law.

Further details of the analysis, a table of $\zeta(z)$, and additional examples of the application of the method, will be included in a paper, "The Boundary Layer and Skin Friction for a Figure of Revolution at Large Reynolds' Numbers", to be published soon in Publication No. 2 of the Daniel Guggenheim Airship Institute.

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Light Alloy Propeller Blades

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(Received August 22, 1934)

A short introductory history describes the early efforts made toward producing a light alloy aircraft propeller up to the year 1922, when the first blades were successfully made by the drop forging process.

The chemical composition and mechanical properties of the propeller blade alloy are given together with a description of the various steps in processing the cast ingots in order to obtain uniform properties throughout the blanks. In the actual fabrication of the propeller blades the working is so carried out that the metal fibers are developed parallel to the blade edges and surface. This makes for maximum uniformity and reliability in service and requires that the propeller blade be finished from the original piece of cylindrical stock with the production of almost no forging flash. Illustrations are included to show the character of the metal flow in the blade forgings.

Etching, heat treatment, and inspection are described and in conclusion some comment is offered upon the present state of development of magnesium base alloy propeller blades both as to material and methods of fabrication.

IT is the purpose of the present article to report the progress made during the past few years in the production of light alloy propeller blades from the standpoints of material and methods of fabrication. It is not considered within the province of the report to comment upon any of the aspects of propeller blade design, manufacture, or service. A short introductory history of the metal propeller may be of interest and assistance in visualizing the present state of development and in understanding some of the problems which were involved in advancing the art thus far.

HISTORY

The first serious effort looking toward the production of a practical light alloy propeller blade was made in 1917–1918 as a result of the war-time demand for a more permanent blade than could be made from wood, coupled with the fact that the newly commercialized "duralumin" alloy offered, for the first time, a light metal having physical properties which seemed adequate to meet the requirements of propeller blade service.

The first attack on the problem was made on the basis of forming the front and rear blade surfaces from tip to tip in two pieces of heat-treated duralumin sheet. These two formed sheets were then placed together in a jig and welded around the edges to produce a hollow blade form. A light alloy hub was then welded in place after which the propeller was finished and balanced. Quarter and half size models of this construction were produced and tested. The welding difficulties involved, however, proved to be very serious and although some progress was made, the end of the War resulted in the work being discontinued. The problem was not revived again until 1922. In this four year interval the process of making strong alloy drop forgings had been developed, based upon a modification of the original duralumin composition, which lends itself easily to this type of manufacture and which can be heat-treated to possess excellent mechanical properties. This alloy and method of fabrication being now available, the attempt was made to forge the propeller blades solid, both individually and in pairs having a hub section in the center. Due to the fact that only moderate sized forging equipment was available at the time, the dies could only be made long enough to reach part way toward the tip of the blade. The remaining portion was drawn out under flat dies, leaving sufficient stock for finishing operations. While the method was laborious, the resultant product met with almost instant recognition as marking a long step in the advance of aeronautical science. From this date onward the light alloy propeller blade has been the subject of the most intensive study and investigation both as to fabrication and as to design. While the original alloy, except for slight modifications, is still being used, the process of manufacture has been studied step by step back to the original ingot with the result that each operation involved is now subjected to uniform control and inspection.

The material used in these blades is the Aluminum Company of America's alloy 25-ST

having the following approximate chemical composition and mechanical properties:

Chemical Composition

Copper—4.5%; Silicon—0.8%; Manganese—0.8%; Aluminum—92% (min.)

Mechanical Properties

Ultimate Strength—58,000 lbs. per sq. in.; Yield Strength—35,000 lbs. per sq. in.; Elongation in 2"—20%; Brinell Hardness—100 (500 kg. load—10 mm ball); Impact (Izod) 7.5 ft. lbs. for standard specimen; Fatigue Limit—15,000 lbs. per sq. in.

Preparation and Inspection of Stock

In order that these mechanical properties may be realized in all parts of the finished blade forging, it is necessary that the original ingot should be of large enough cross section so that the shank portion of the blade may receive a sufficient amount of reduction to thoroughly break down the cast structure and to render the metal capable of attaining its potential physical properties. An ingot weighing as little as 100 pounds contains sufficient metal to produce an ordinary 5 foot propeller blade, but uniform physical properties cannot be obtained in a blade made from such a small ingot because it is not possible to get sufficient work into the heavy shank section which, in service, must carry a tremendous centrifugal load. Such a blade would have good physical properties at the tip which would become progressively worse as the section increased in the direction of the shank. It has been found that 80 percent reduction in cross section is the minimum required to produce uniformly reliable properties throughout the blade and this has led to a minimum ingot weight of 1000 pounds, having a minimum cross section of 150 square inches. Ingots weighing as much as 2500 or 3000 pounds having cross sectional areas as high as 400 square inches are sometimes used. The most careful melting and casting practice is required to produce aluminum alloy ingots of this size free from dross and internal defects.

Three methods of breaking down the cast ingot into forging stock have been investigated, namely, drawing between flat dies, extrusion, and rolling. The first named method produces a good grade of stock, but is impractical commercially on account of the time and expense involved. The extrusion method, particularly in the larger sizes (4 to 6" rounds) does not give a uniform structure; the metal immediately in front of the die opening receiving relatively little work which results in varying physical properties from one end of the bar to the other. Rolling, on the other hand, is an economical method and has the additional advantage of producing a uniform fibre particularly desirable in propeller blade stock. The cast ingots are worked down on a large blooming mill to 6" squares after which the stock is scalped, inspected, and finished on a structural mill to a round bar of the desired size. It must then pass a rigid inspection before being accepted as propeller blade stock. This inspection for roundness, straightness, surface condition, etc. includes an examination of the fracture at the end of each piece from which a propeller blade is to be fabricated. To the experienced observer the appearance of the fractured bar is highly significant. There is almost no defect in the original ingot or any abuse in subsequent manufacturing operations which does not show up in the fracture of the rolled bar. This makes possible a virtual elimination of defective stock before the start of the actual process of blade fabrication.

Blade Fabrication

Experience has indicated the desirability of producing a definite "flow line" or "fiber" structure in propeller blade forgings. Such a structure is of course the result of elongating the grains by the processes employed in working. These flow lines should not cut the contour of the blade edges but should run parallel to them, converging from the broad section at the base of the blade toward the narrow section at the tip and spreading likewise from the shank section into the broad portion. This structure is illustrated in sections 1–2–3–4 of Fig. 1 which are enlarged views at stations similarly lettered on blade at top which has been sectioned longitudinally from hub to tip.

To produce such a structure requires a highly specialized manufacturing process which shapes the blade with the very minimum of forging

flash and so keeps the whole fiber structure intact and practically contained within the contour of the blade edges. This is accomplished in three distinct steps, the first of which upsets the shank section and extrudes a small tonghold, eventually used as a test coupon, furnishing a permanent record of physical properties on each blade manufactured. No flash is involved in this operation. The second step consists in taper and form rolling the blade section proper. In this operation the general blade shape is obtained and the flow line and fiber structure is developed in the manner already referred to. No flash is involved in this operation. The third operation consists in bringing the blade to its final dimensions in dies under a large drop hammer. If the previous steps in the process have been carried out properly, very little forging flash will be produced under the hammer and the fiber lines will remain intact.

Controllable Pitch Propeller

The blade for the controllable pitch propeller is of particular interest from the standpoints of moving a considerable volume of metal without producing any forging flash or disturbing the continuity of the metal fibers. Fig. 2 shows a controllable blade sectioned longitudinally through the shank. The cylindrical shank is pierced to receive the control member and at the same time expanded to form a seat for the annular thrust bearing which is slipped over the shank before the piercing and expanding operation is performed. It is only required then to machine a seat for the thrust bearing and slip it back into place. It will be noted how the metal fibers follow the irregular shank contour in continuous lines, thus offering the greatest resistance to stresses encountered in service.

Etching, Heat Treatment and Final Inspection

The next step in the process consists in caustic etching to remove oil and grease in order to facilitate final inspection of the surface for any possible flaws after which the blades are ready for heat treatment. The heat treatment process is carried out in electric furnaces automatically controlled within a range of plus or minus 10°F. Great care must be exercised in handling the blades in order to keep them straight while heat-

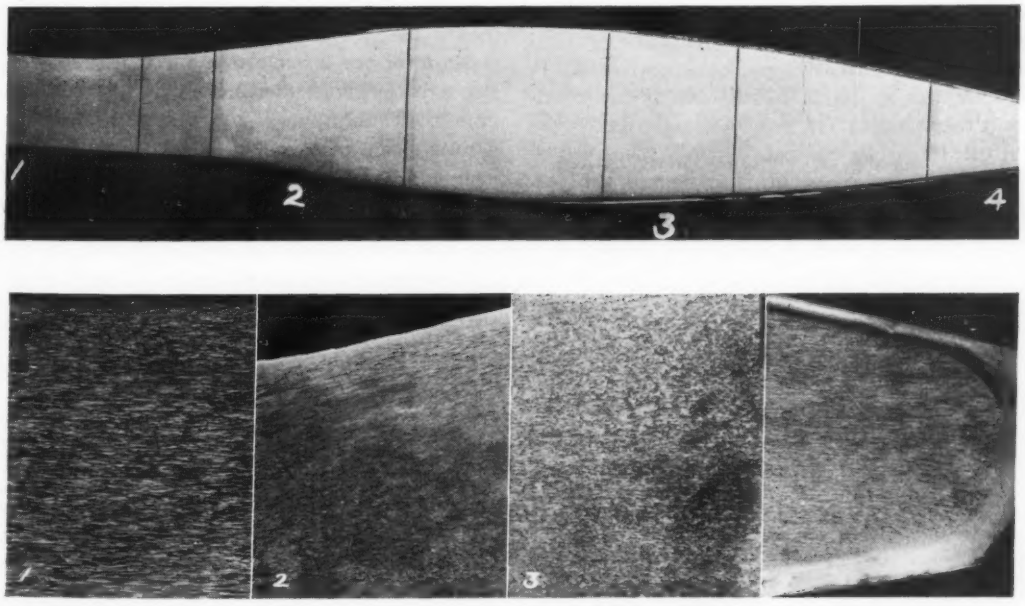

Fig. 1.

FIG. 2.

ing, as well as to insure uniform quenching. This is accomplished by suspending the blades individually. The precipitation hardening or final step in the heat treating process is carried out in steam tanks at about 310°F. After heat treatment the test coupons, previously referred to, are cut off. Each blade is permanently identified so that its physical properties may be referred to at any time in the future, after which it is ready for shipment to the propeller manufacturer.

MAGNESIUM ALLOY PROPELLER BLADES

Some mention should probably be made here of the progress to date in the use of magnesium base alloys for propeller blades. Such progress has been slow, first, due to the fact that until quite recently no magnesium alloy was available which appeared to have mechanical properties sufficient to warrant its use in propeller blades and, second, because the processes required for working the most promising alloys are much more difficult and expensive than those required for handling the aluminum base alloys. The only successful method of producing high strength magnesium alloy blades at the present writing is by the process known as hot pressing, which consists of working in comparatively crude dies under a hydraulic press capable of exerting tremendous pressure. Magnesium alloy blades have been produced both here and abroad by this method, although of course much more stock must be left on them for machining than is required in the case of aluminum.

The principal advantage of magnesium as a propeller blade material is its low specific gravity which is about two-thirds that of aluminum. This, of course, reduces the centrifugal loading in a magnesium blade but the gain is partially offset by the necessity of increasing sections to compensate for the lower elastic modulus and yield strength of magnesium as compared with aluminum. It would appear, however, that the magnesium blade may make a real place for itself, particularly in the larger diameter propellers for geared engines where the weight saving will show to the greatest advantage.

Book Reviews

Aerodynamik, by Prof. Dr. R. Fuchs, Prof. Dr. L. Hopf and Dr. Fr. Seewald; Vol. I, Mechanics of the Airplane, by Prof. Dr. L. Hopf; Julius Springer, Berlin, 1934; 339 pages.

This is the first of a series of three volumes dealing with aerodynamics which is to supersede the earlier volume on the same subject by the two authors, Fuchs and Hopf. The second and third volumes, which will appear within the next year, will deal with the "theory of aerodynamics" and "propellers"and are written respectively by Fuchs and Seewald.

This first volume is composed of seven chapters, each of which treats a different phase of airplane design. The first chapter deals with the elementary lift and drag equations of the wing and propeller. It also discusses experimental methods of measuring free flight and model tests. In the second chapter the performance characteristics with power on and off are evaluated, and there is an excellent section on the changes of density and temperature with altitude and their effect on performance.

The next chapter, which is described as "numerical values," contains a comprehensive section on weights, with numerous graphs of characteristic airplane weights. There are also very complete sections on the lift and drag of airfoils, the parasite drag of airplane parts, and the interference drag due to variation of location of parts. The next part of the chapter goes into a detailed discussion of the cowling of air cooled radial engines, and their effect on the speed of the airplane. The resistance of boat hulls is included in the chapter, and a resumé of propeller characteristics completes it.

Pitching moment equations in straight flight from a statical viewpoint comprise the fourth chapter. First the wing moments are derived, then the tail moments, these being discussed with considerable detail, and finally the effect of slipstream is introduced. The moments acting on the airplane as a whole are examined as to the degree of stability.

Chapter five deals with disturbed and controlled longitudinal motion. In it the stability equations are developed and their solution discussed. A thorough examination is made of the resultant motion of the airplane under varying degrees of static stability and control. The motion with power on and power off and stability in stalled flight is then discussed.

The sixth chapter deals with lateral stability of the airplane, studying first the static viewpoint in which the moments due to roll and yaw are developed. The force and moment equations for various flight conditions are evaluated and explained.

In the last chapter dynamic lateral stability is investigated. The equations of stability are developed, and the meaning of the roots are explained; it ends with an excellent discussion on the stable and unstable lateral motions that the airplane may experience.

The book is recommended to any one interested in airplane design who has a reading knowledge of German, as it contains a thorough and comprehensive study of the mechanics of the airplane, and combines in a single small volume a large amount of practical and theoretical information.

AUGUST ZINSSER, JR.

Aerodynamic Theory, Dr. William Frederick Durand, Editor-in-Chief; Vol. I, Mathematical Aids, by W. F. Durand; Fluid Mechanics, Part I, by W. F. Durand; Fluid Mechanics, Part II, by Max M. Munk; Historical Sketch, by R. Giacomelli and E. Pistolesi; Julius Springer, Berlin, 1934; 398 pages; 20 marks.

This volume is the first of a series of six on the general field of aerodynamics which is appearing under a grant of the Guggenheim Fund for the Promotion of Aeronautics. To quote from its preface, Volume I "is largely taken up with material dealing with special mathematical topics and with fluid mechanics. The purpose of this material is to furnish, close at hand, brief treatments of special mathematical topics which, as a rule, are not usually included in the curricula of engineering and technical courses and thus to furnish to the reader, at least some elementary notions of various mathematical methods and resources, of which much use is made in the development of aerodynamic theory." The principal developments, of course, will appear in the other five volumes which will cover the mechanics of perfect, viscous and compressible fluids, the applied theory of wings and propellers, the dynamics of airplanes and airships and several other topics, including research methods, performance and cooling. Some twenty-five authorities are contributing.

As is usually the case with the first volumes of series such as this, two quite different appraisals are possible, depending upon one's point of view. If the volume is judged only on the basis of the material which it covers it is found to be fairly satisfactory. It could hardly be otherwise, however, since the material which it covers has already been well done for the most part and is easily available in familiar volumes. The exceptions are parts of Munk's division on Fluid Mechanics and the historical sketch by Giacomelli. The latter is very creditably done from either point of view and for practical as well as adornment purposes might well have been made the first division of the series. The Durand division on mathematics has a certain elegance which is characteristic of third or fourth generation treatments. On the other hand, from the standpoint of usefulness, certain topics are perhaps overdone, notably the theory of dimensions and the mechanics of conformal transformation, while others are inadequate such as the section on Fourier series. There seems to be a general tendency throughout to over-emphasize manipulations and to underestimate physical interpretation and application. In general, much the same remarks apply to the Durand division on Fluid Mechanics.

The Munk division on three-dimensional fluid mechanics is a fresh and stimulating review of Lamb. Two or three departures, however, are noteworthy. The Hamiltonian rule for scalar multiplication is assumed rather than the more usual Grassmann rule which reverses the signs of

certain terms, the zonal harmonics are derived in an unusual way, and attention is drawn to several new interpretations. As a whole, the section is well done.

On the other hand, if the volume is judged on the basis of its adequacy as a reader's aid for the whole series, it seems likely to be less successful. If this is to be its primary function, then, as the preface states, it should be a general reference in those phases of aeronautical mathematics, mechanics and history which are not easily accessible in standard works, yet are required as illuminating and orienting background for the subsequent divisions. From this point of view, it is likely that the division on mathematics will be found, when the other volumes are completed, to be inadequate for the readers' needs. It seems that fairly complete treatments of determinants, Fourier series, zonal harmonics, a few of the more important integrals and differential equations, would rather certainly have to be included, as well as a consistent treatment of the algebras of the two-dimensional and three-dimensional vector and of the complex number. Also, a new division on rigid mechanics would then likely prove to be necessary as a support for such divisions as "Dynamics of an Airplane" and "Experimental Research in Aerodynamics," and the divisions on fluid mechanics, which are now necessarily redundant with the Kármán division on "General Aerodynamic Theory of Ideal Flow" in the second volume, would take quite different form. It would certainly carry, for example, a much fuller treatment of the atmosphere and a more complete development of fluid momentum mechanics, the former because of its general pertinence and interest, and the latter as a basis for the divisions on "Airplane Propellers" and "Aerodynamic Theory of Airships."

If the latter point of view is the correct one, it appears that Volume I should have been the last volume of the series instead of the first to be written. Obviously the probable difficulties which the average reader is likely to find in the various divisions of the main series cannot be determined until the series is completed and carefully reviewed as a whole.

R. H. SMITH.

Letters to the Editor

The Drag of Tapered Cantilever Airfoils

This paper, by R. H. Upson and M. J. Thompson, in the October 1934 issue of the Journal of the Aeronautical Sciences is a good example of the kind of analysis to which our airfoil data were intended to apply, and we are pleased to feel that we have contributed something to the analysis. The methods followed are in many respects very ingenious, particularly the drag calculations, and I believe sufficiently accurate for purposes of preliminary design. In regard to the weak points of the analysis, little need be said because he shows by recognizing and discussing them in the paper that he appreciates them. While his conclusion that wings should be more highly tapered than current wings is probably correct, I question the advisability of using extreme taper for the following reasons:

(a) The wide root chord may be objectionable, although with good fuselage junctures our tests indicate no increased adverse and possibly some favorable interference.

(b) The span tends to be slightly increased.

(c) Lateral control and stability at the stall are affected adversely as the outer portions of the wing are more likely to stall first.

In general, it should be pointed out that the method of comparing wing-drag coefficients for wings of equal structural efficiency tends to exaggerate the differences. Actually the designer in selecting from wings of different taper ratios would compare wings having more nearly the same section thicknesses and attempt to allow for the increased weight of the wings with low structural efficiencies. The weight increase would undoubtedly be much less detrimental than the drag increase associated with increased section thickness.

E. N. JACOBS

National Advisory Committee
for Aeronautics.

The Sylvanus Albert Reed Award

Dr. S. A. Reed, a Fellow of the Institute, has provided the I. Ae. S. with an award which will give recognition to the outstanding work in the aeronautical sciences.

Dr. Reed has agreed to provide a certificate and $250 a year during his lifetime and endow the award with a legacy of $10,000 which will provide for the future.

In his letter making the gift he states the terms of the award which show the scope of the work for which the award will be given.

"The Award is to be given, preferably annually, for the greatest advance in the aeronautical sciences resulting from experimental or theoretical investigations, the beneficial influence of which on the development of practical aeronautics is apparent."

The recipient of the Award is to be selected by majority vote of the Fellows. Charles L. Lawrance, J. C. Hunsaker and Lester D. Gardner have been selected by Dr. Reed to administer the award and the fund.

Dr. Reed, who developed the duraluminum airplane propeller which has largely supplanted the wooden propeller, was born at Albany, New York, April 8, 1854. He attended Columbia University where he received five degrees including those of Doctor of Philosophy and Doctor of Science. He later studied in the physical laboratories at the Universities of Wurzburg and Berlin. After a professional career as an engineer in many fields, he invented and developed the Reed metal propeller which is licensed for manufacture in many countries. Dr. Reed was awarded the Collier Trophy for 1925.

Organization Meeting of the Pacific Coast Section of the Institute of the Aeronautical Sciences

About 180 members and guests of the Institute of the Aeronautical Sciences attended the first meeting of the newly formed Pacific Coast Section, held at the California Institute of Technology in Pasadena, on the evening of December 4, 1934.

As the membership of the Institute grows, other sections will be organized in centers where there are a sufficient number of members to permit the holding of well attended local meetings. Through the activity of these sections, members who cannot attend the Annual Meetings at Columbia University in New York will have the opporsunity of hearing interesting speakers at meetings of the sections to which they belong. When distinguished foreign members of the Institute visit centers where there are sections it is believed that members will enjoy having them tell of their special interests in the aeronautical sciences.

At the dinner in the Athenaeum, the attractive social center of C. I. T., Donald W. Douglas, Vice-President of the I. Ae. S., gave a sketch of the purposes of the Pacific Coast Section, commenting on the efforts of Dr. Clark B. Millikan in the organization of the group. Lester Gardner, Secretary of the Institute, who had flown from New York to attend the meeting, brought greetings from President Lawrance, and complimented the group on the fact that the meeting was even better attended than the annual dinners in New York. He disclosed that: the Institute has in some respects already reached a membership comparable to that attained by the Royal Aeronautical Society after sixty-eight years of existence; that dues for 1935 are now 60% paid up; that the Journal will be issued bimonthly; that the Institute has championed the cause of the aeronautical engineer before the Federal Aviation Commission; and that Dr. S. A. Reed is endowing the award of a certificate of merit and $250 each year for the greatest achievement in the aeronautical sciences. Dr. Millikan expressed the hope that from three to five meetings of the Section might be held each year, and stressed the point that informality and active discussion of current aeronautical problems were desired. He announced also that no additional sectional dues would be expected from members.

At a short business meeting following the dinner, the following members were elected to serve on an executive committee for one year for the purpose of organizing the Pacific Coast Section: C. L. Egtvedt (Boeing Airplane Company); Donald A. Hall (Hall Aeronautical Development Co.); Hall L. Hibbard (Lockheed Aircraft Corporation); Clark B. Millikan (California Institute of Technology); John K. Northrop (The Northrop Corporation); Arthur E. Raymond (Douglas Aircraft Company, Inc.); Elliott G. Reid (Stanford University); Gerard Vulete (Airplane Development Corporation); Baldwin M. Woods (University of California).

It was also announced that for the present, the mailing address of the Section would be: Pacific Coast Section of the I. Ae. S., c/o Aeronautics Department, California Institute of Technology, Pasadena, California.

It was requested that members send suggestions regarding future pans for the Section to this address.

After the dinner a technical meeting was held in the lecture hall of the Gates Chemical Laboratories. Four papers were presented and discussed:

C. L. Johnson, Aerodynamics Engineer of the Lockheed Aircraft Corporation, in a paper entitled "Longitudinal Stability of Bi-motored Aircraft," presented results of a most comprehensive series of wind tunnel and flight tests on stability characteristics of a low wing transport. This paper dealt with the various aspects of the problem of longitudinal static stability of a modern transport plane. Fillets, wing flaps, and other factors affecting tail efficiency were discussed. A comparison was made of wind tunnel and flight test data on stability. The problem of nose-heavy loading conditions was taken up briefly.

W. C. Rockefeller, Teaching Fellow, California Institute of Technology, outlined his method of flight path control for minimum time and greatest economy, in a paper "Optimum Flight Path in Air Transport Operations." This method is now being tested under service conditions by T. W. A., Inc. The author described a rapid graphical means of determining the flight path which should be followed by the pilot in order to make a given trip in the minimum possible time. The method included variations in both the airplane performance and the wind distribution over the course. Also included was a means for determining the cruising power required to complete a given flight in scheduled time.

A. V. Stephens, Fellow of St. John's College and recently with the British Air Ministry, dealt with "Spinning Researches at Farnborough," and after reviewing the development of the spinning problem, outlined the results of his full-scale and free-spinning wind tunnel tests. The paper dealt with an investigation into the difficulty experienced in recovering from spins on certain aeroplanes. Full scale experiments were first described. These led to the conclusion that satisfactory spinning properties could best be obtained by providing adequate resistance to rotation about the normal axis. This could be done by raising the tailplane. The development of a technique for experimenting with small dynamical models in a vertical wind tunnel was then outlined. This method had been applied to *ad hoc* testing of some twenty new designs, with encouraging results.

F. R. Collbohm, Flight Test Engineer, Douglas Aircraft Co., Inc., discussed "Flight Test Engineering," giving the problems involved and stressing the importance of the use of motion picture records, after which he exhibited a series of motion pictures taken in tests for landing speeds and in dives, pull-ups and sharp turns. The discussion on flight testing was limited to a short description of four representative tests: (1) The measurement of landing speed by using a

standard motion picture camera mounted in the airplane. (2) Plotting water takeoff drag curves of a flying boat under various load and C.G. conditions. (3). Determination of the load deflection curve of an airplane wing by flight test. (4). Use of a motion picture camera to obtain dive test records.

At a subsequent meeting of the Executive Committee, a quorum being present, the following officers of the Pacific Coast Section were elected to serve for the year 1935:

Chairman: Clark B. Millikan
Vice-Chairman: Hall L. Hibbard
Secretary: William C. Rockefeller

Annual Meeting of the I. Ae. S.

The Annual Meeting of the Institute will be held at Columbia University on January 29–30, 1935. In addition to the meeting of members, technical sessions will be held during the two days; a smoker will be held at which interesting moving pictures presented by the National Advisory Committee for Aeronautics will be shown, new aeronautical equipment will be exhibited, and the Annual Dinner of members will conclude the gathering of members.

At the Annual Meeting, the reports of the officers for the past year will be read, new members of the Council will be elected, and an opportunity given to members to discuss the activities of the Institute.

Below is a tentative program which will indicate the scope of the subjects to be discussed at the meeting.

TUESDAY, JANUARY 29, 1935

Meteorology—10:00 A.M.
Chairman: Dr. W. R. Gregg, Chief, U. S. Weather Bureau.

Radio—11:30 A.M.
Chairman: Dr. Lewis M. Hull, President, Aircraft Radio Corp.

Luncheon—1:00 P.M.
(At the Faculty Club.)

Instruments—2:15 P.M.
Chairman: Capt. A. F. Hegenberger, Air Corps, Wright Field.

Metallurgy—4:00 P.M.
Chairman: Prof. Alfred V. de Forest, Assoc. Prof. Mech. Eng., M. I. T.

Smoker—8:00 P.M.
(At the Faculty Club.)
Film showing air flow about models in the N. A. C. A. smoke tunnel—Presented by Mr. Eastman N. Jacobs.
Film showing the compressibility burble in the N. A. C. A. high-speed tunnel.
High-speed moving pictures showing the effect of air-fuel ratio on combustion in a compression ignition engine—by Mr. A. M. Rothrock.

WEDNESDAY, JANUARY 30, 1935

Aerodynamics—10:00 A.M.
Chairman: Dr. Clark B. Millikan, Associate Prof. Aeronautics, Calif. Inst. Tech.

Luncheon—1:00 P.M.
(At the Faculty Club.)

Power Plants and Fuels—2:00 PM.
Chairmen: Prof. C. Fayette Taylor, Prof. Automotive Eng., M. I. T.; Dr. Graham Edgar, Director of Research, Ethyl Gasoline Corp.

Annual Meeting of the I. Ae. S.—5:00 P.M.
Chairman: Mr. Charles L. Lawrance, President of the I. Ae. S.

Annual Dinner of the I. Ae. S.—7:00 P.M.
(At the Faculty Club.)

Donald W. Douglas to give Wilbur Wright Memorial Lecture

The Royal Aeronautical Society invited Donald W. Douglas, a Fellow of the Institute, to deliver the twenty-first Wilbur Wright Memorial Lecture in May, 1935. He has accepted and will discuss the development of high speed air transport. This lecture is given by an American every other year, alternating with lecturers from other countries.

The lecture is usually given in London at the South Kensington Museum. The speaker is honored by a dinner before the meeting, to which a distinguished group, including the Council of the Royal Aeronautical Society, is invited. The speaker delivers the lecture standing under the original Wright airplane, surrounded by one of the finest aeronautical collections in the world. The invitation to Mr. Douglas to give this lecture is another evidence of the interest the Douglas DC-2 air transport airplane has aroused in Europe.

Gifts

The Aluminum Company of America has presented to the Institute the Aluminum chairs which it had previously loaned for use at the Skyport. These thirteen chairs were specially made to match the blue and aluminum decorations.